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Magnetic Amplifiers

A RISING STAR
IN NAVAL ELECTRONICS

ELECTRONICS DESIGN &
DEVELOPMENT DIVISION

DEPARTMENT OF THE NAVY BUREAU OF SHIPS
WASHINGTON 25, D. C.

MAGNETIC AMPLIFIERS

A Rising Star in Naval Electronics

Prepared by
Electronics Design and Development Division

Bureau of Ships
Department of the Navy
18th and Constitution Avenue Washington 25, D.C.

Navy Department
Bureau of Ships
Washington 25, D.C., 1 August 1951

1. "Magnetic Amplifiers---" - NavShips 900,172, is an unclassified publication which describes "an old device in a new suit." The device is the saturable core and the new suit is the core's use in electrical and electronic applications.

2. This pamphlet was published previously in small quantities for limited distribution. A more detailed technical description of the material is included in the June and July 1951 issues of the BuShips Electron.

3. This material is published to encourage the use of the device in electrical and electronic applications where reliability of performance is the prime consideration. A review of machinery application principles is included as an aid toward understanding the general principles of the device.

4. Extracts may be taken from this publication to facilitate the preparation of other Navy instruction books, pamphlets, and handbooks.

5. Requests for additional copies of this publication should be addressed to the Bureau of Ships.

H. N. WALLIN
Rear Admiral, USN
Chief of Bureau

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Design Engineers Please Note

This publication is not intended as an engineering manual. Mathematics and detailed circuitry was deliberately removed to simplify the presentation in a form easily assimilated by busy engineers who often do not have the time to study the more detailed technical papers previously presented on the subject. A bibliography is included for those who wish to study the material in detail.

MAGNETIC AMPLIFIER

A RISING STAR IN NAVAL ELECTRONICS

INTRODUCTION

Naval Electronics engineers are beginning to accept the fact that a competitor to the electron tube, in the power and control field, has not only penetrated their domain but is here to stay. When first confronted with this device they simply ignored it as being an impostor -- too slow, cumbersome and inefficient to be taken seriously. Even when it started to strut in a new cloak of self saturation and promoted itself to the rank of magnetic amplifier, it was still ignored by American electronic engineers. The device finally gave up in disgust and proceeded to Germany for physical reconditioning, and a post-graduate course in military and social education.

The electrical machinery people early visualized the advantages of the device as attested by the almost universal application of this static control for rotating equipment.

Electronics engineers are now forced to concede recognition of the magnetic amplifier, as it has demonstrated its value beyond question in many fields previously dominated by electron tubes.

The significance of this development in relation to Naval engineering is better appreciated when it is realized that this component is applicable to almost everything that rotates or moves on a fighting ship -- from throttle controls on the main engines -- speed, frequency, voltage, current and temperature controls on auxiliary equipment -- fire control, servo mechanisms, and stabilizers for guns, radar and sonar equipment -- pulse forming, sweep multivibrator circuits for radar, loran, and transponder equipment, to computers, course and speed plotters to verify the results.

The device is ideally suited to submarine and aircraft equipment because of the extreme voltage fluctuations of the prime power sources. Numerous countries have contributed to its evolution.

HISTORY

The magnetic amplifier is not new -- the principles of the saturable core control were used in electrical machinery as early as 1885 although they were not identified as such.

Saturable core devices have been used, principally in heavy electrical machinery, in the United States since 1900. The U. S. Navy has been using them to a limited extent mostly as static control instruments in rotating equipment during the past eight years; development beyond this perimeter into the electronic field has been retarded in the United States primarily due to the reluctance of our engineers to experiment with a new device, especially in view of the excellent performance experienced with current electron tube equipment.

Many engineers are under the impression that the Germans invented the magnetic amplifier; actually it is an American invention. The Germans simply took our comparatively crude device, improved the efficiency and response time, reduced weight and bulk, broadened its field of application, and handed it back to us.

It was mainly the improvement in processing magnetic material and the introduction fo selenium rectifiers that led to the wide use of the magnetic amplifiers by the Germans.

The German navy used the device in its master gun stabilizers; their air force used it in automatic pilot and ground approach systems. They also used it in servo and frequency control systems for long range rockets, blind landing aids, and to regulate the fuel flow in relation to atmospheric and ram pressure in some types of guided missiles. They also applied the device as cathode followers, replacing electron tubes in computer circuits. The German army had started to apply it to the V-2 rocket stabilizer and steering system.

German civil interests were also quick to visualize the advantages of this device. They had started to apply it to computing machines, electric brakes for trucks and locomotives, high voltage power lines (controlling up to 50,000 KVA), a-c streetcar controls and other miscellaneous uses.

The fact that the Germans introduced the device into fields previously dominated by electron tubes is considered by many to be of as great importance as the technical development of the device.

Although Germany is unquestionably responsible for the rebirth of the magnetic amplifier, other countries (especially the United States) held a considerably greater number of patents on this device. The efforts of Sweden, England, and Japan were also considerable.

The reason for the Nazis assigning their best scientists and expending millions on its development in the midst of a bitter war has never been definitely determined. There was no shortage of electron tubes; performance of the tube-controlled equipment certainly was not improved by the substitution of this device.

Considering the above, the motive warranting such expenditures appears to have been an acute shortage of field electronics technical personnel, making a dependable, maintenance free device mandatory wherever possible.

The performance of the magnetic amplifiers obviously must have equaled that of the electron tube circuits as these devices were used in some very critical applications, such as stabilizers, servos, and fire control equipment in their finest fighting ships.

It was during the last war that the U. S. Navy started to exploit the device for purposes other than power regulators. Development contracts have now expanded into the high speed range of digital computers and pulse forming, memory and scanning applications in radio, radar and sonar equipment.

A magnetic amplifier is simply another type of control valve. A valve in a water line can be considered an amplifier, if a small stream of water operates a larger valve in the main line.

Electrically the device can be compared somewhat to that of an electron tube, in that the grid of the tube controls a relatively large amount of plate power. In a M/A, power is varied, like the water valve and the tube, by inserting the device in series with the load to be controlled. Control is then accomplished by varying this impedance, which increases or decreases the power to the load. The impedance to the flow of AC is effected by changing the degree of saturation with a relatively small amount of DC, or properly phased AC, through a separate winding on the same core. An unsaturated core has a relatively high impedance to AC. A saturated core acts effectively as an air core, with practically no impedance except for the ohmic resistance of the copper wire.

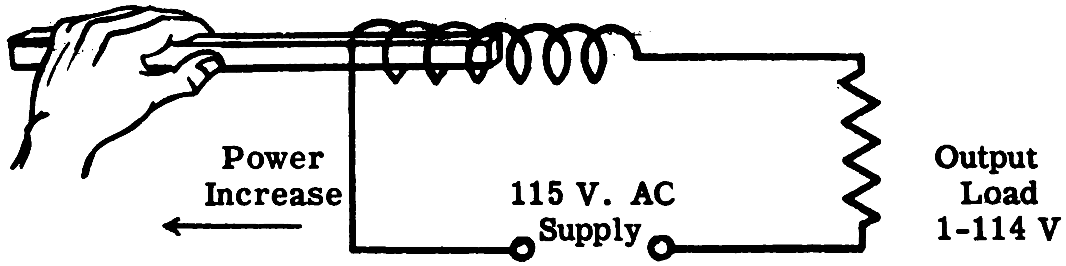
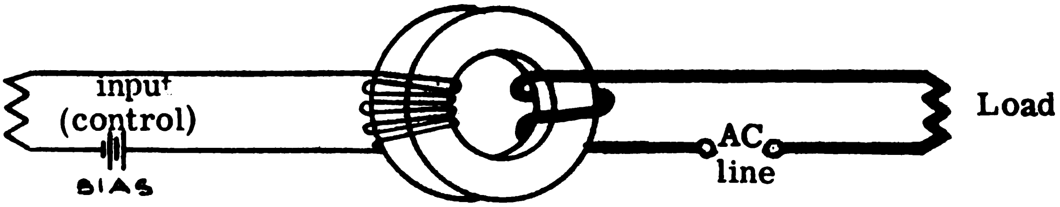


Figure 1

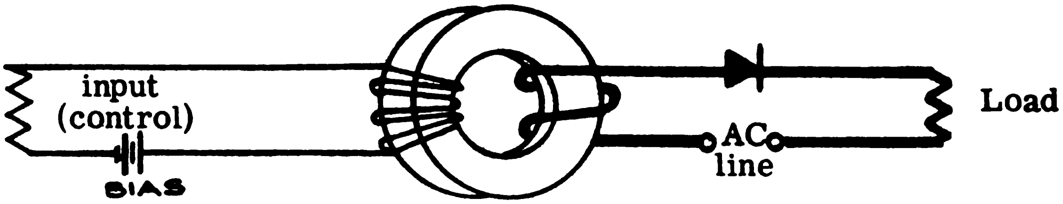
Figure 1 illustrates the principle of operation. With the core completely within the coil the impedance to the flow of current is high -- permitting possibly only a fraction of a volt to appear across the load. Pulling the core out causes this load voltage to rise progressively to practically 115. In effect this is the operating principle of a magnetic amplifier. Since it took only a few watts of muscular energy to move the core within the coil, which may in turn control several horse power, the device is an amplifier. Since this is done magnetically, the device is called a magnetic amplifier.

Technically, it may be described as essentially a device which controls the a-c reactance of a coil by controlling the effective permeability of the magnetic material upon which the coil is wound.

Although the sketch in Figure 1 is drawn primarily to illustrate the principles of operation, there are many applications still in use utilizing the mechanical system. The principle of control is the same; the action, however, does not completely fulfill the description in the previous paragraph "controlling the effective permeability of the magnetic material" since iron in this instance is actually replaced by air. In modern applications the core is stationary; its impeding effects to a-c power is changed by varying the saturation of the iron core. This not only simplifies the installation but permits a much higher speed of response and considerably widens the range of applications.



SATURABLE REACTOR
Fig. 2



MAGNETIC AMPLIFIER
Fig. 3

Figure 2 is the basic circuit of the saturable control. The secondary or load winding impedance is controlled by the amount of current flowing in the primary or control winding. This would be a relatively inefficient amplifier because the control winding ampere turns must be equal to the load A/T plus sufficient A/T to saturate the core.

In Fig. 3 a rectifier is inserted in series with the load. This results in unidirectional load current which assists the control winding in saturation. Considerable less control power is now required, making the device highly competitive with other types of amplifiers.

Although Fig. 3 has been developed into a high gain amplifier it is still deficient in some respects, namely:

1. The device as shown would act as a step up transformer in reference to the load power, and generate power into the control winding. This would not only be undesirable but would also result in an unnecessary power loss.

2. Due to the single rectifier, only an inefficient pulsating DC load power would result.

BASIC CIRCUITS

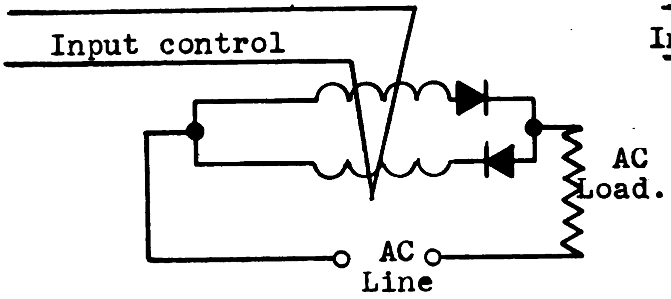


Fig. 4

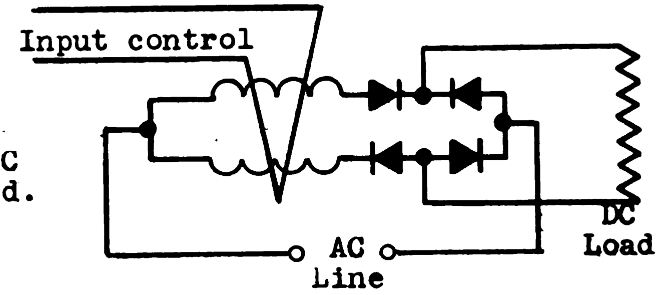


Fig. 5

Figures 4 and 5 show a more practical design. (To simplify the sketches, cores will be taken for granted, control windings will be represented by a single turn.) With two load coils they can be wound opposed, neutralizing any transformer effect into the control coil. The two power coils also permit utilization of both sides of the alternating current, resulting in good wave form and efficiency. Figure 4 is the basic amplifier for AC loads. With the addition of two rectifiers, (5), the device generates and controls a DC load from an AC supply. Three legged cores, with the control coil wound on the center leg, and power coils on outside, are usually used with the above circuits in power control applications.

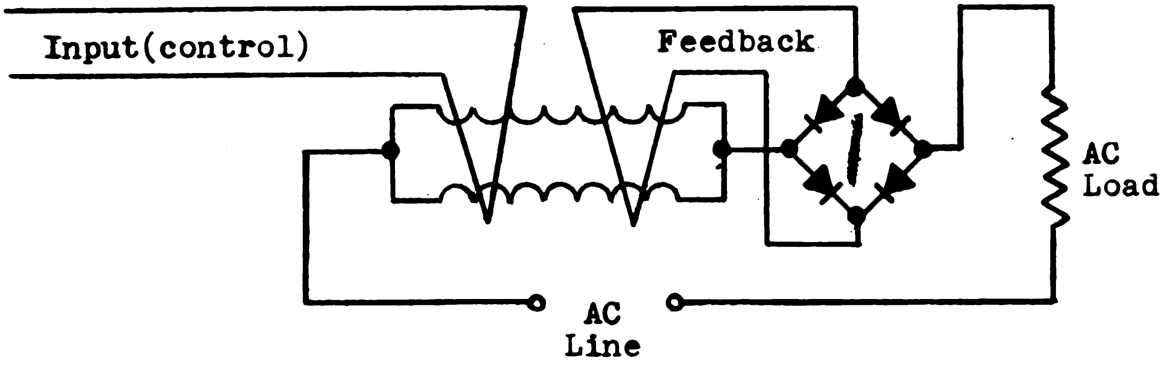


Fig. 6

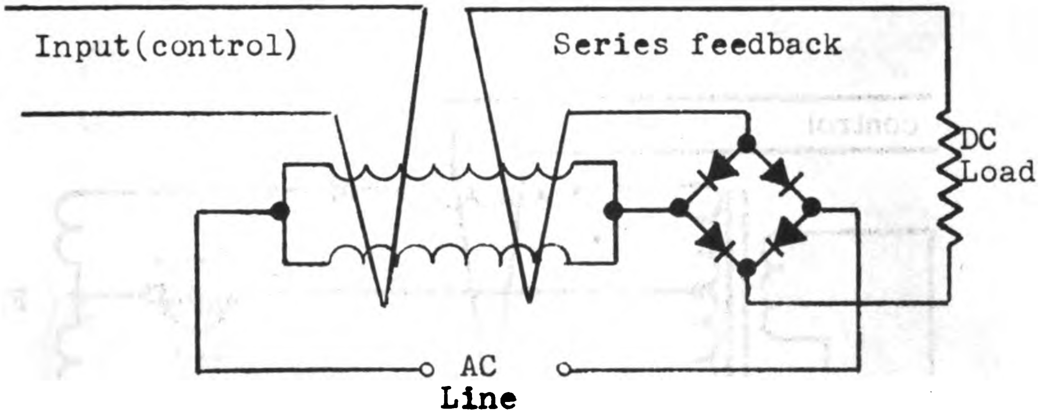


Fig. 7

Figures 6 and 7 show further developments with the addition of feed back. These are identified as external feedback. Gains up to several million per stage have been obtained with these circuits.

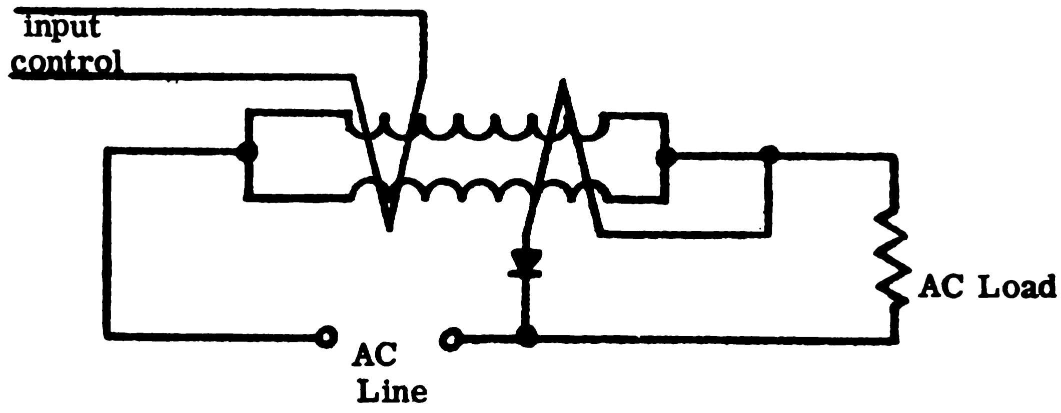


Fig. 8

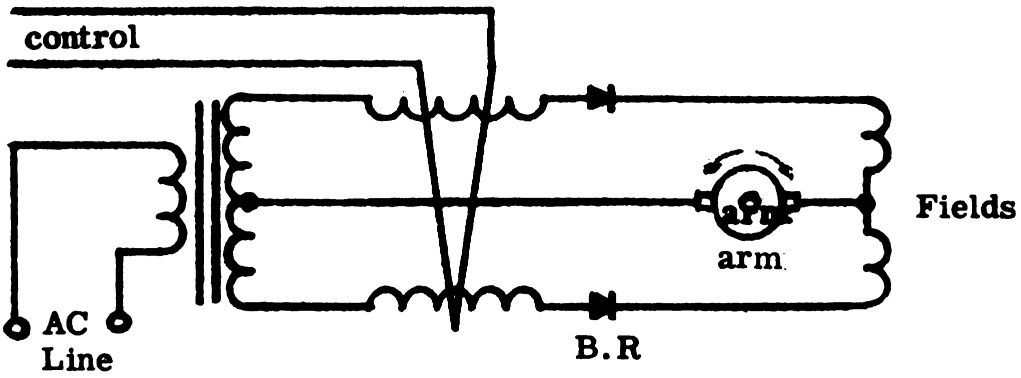


Fig. 9

Figure 8 is a sketch drawn originally for school purposes showing how this amplifier can be used without the load power passing through a rectifier; Figure 9 applied to variable speed reversing motor.

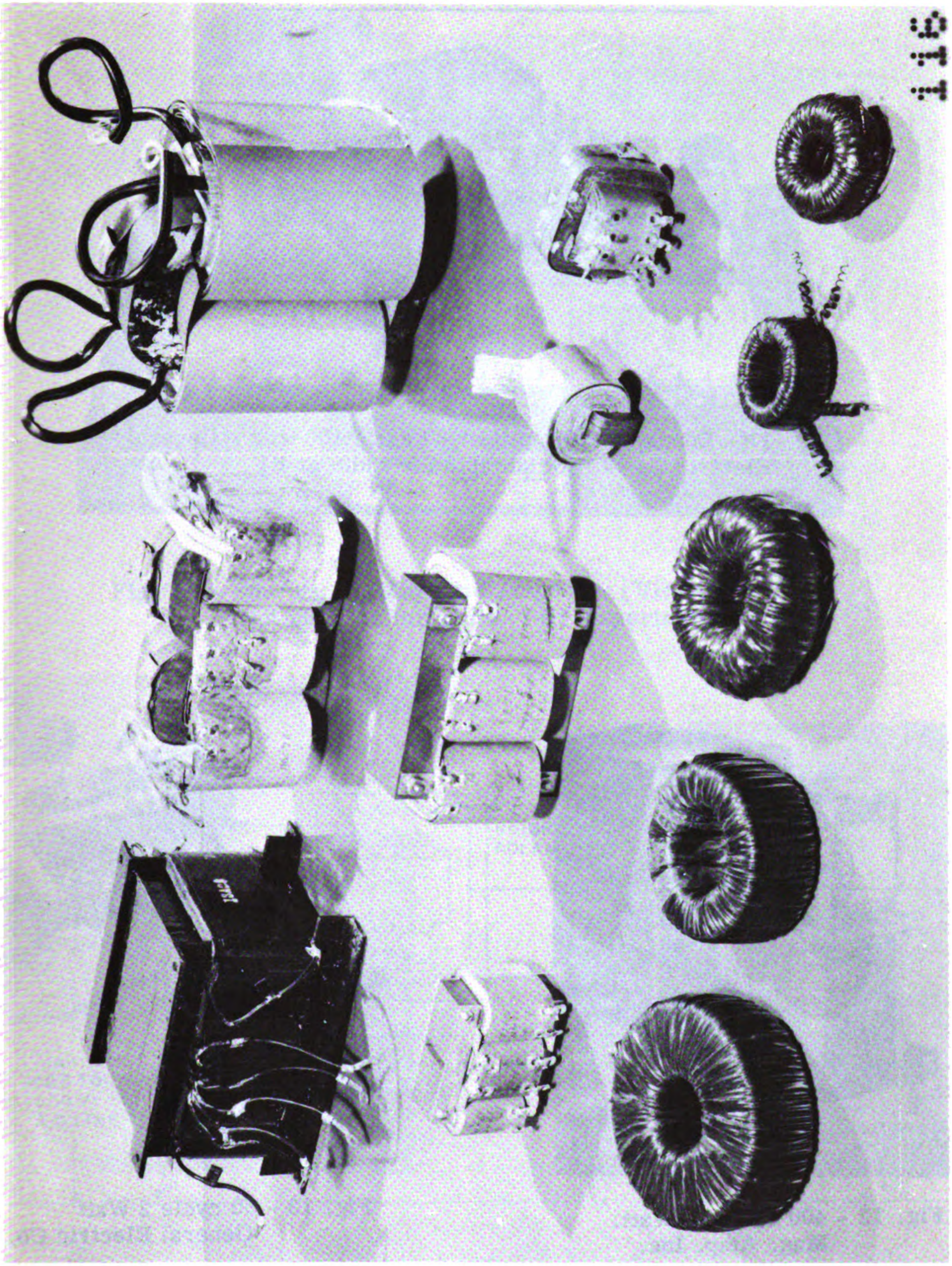


Figure 10 shows various types of saturable reactors used for machinery control applications (Vickers Inc.)

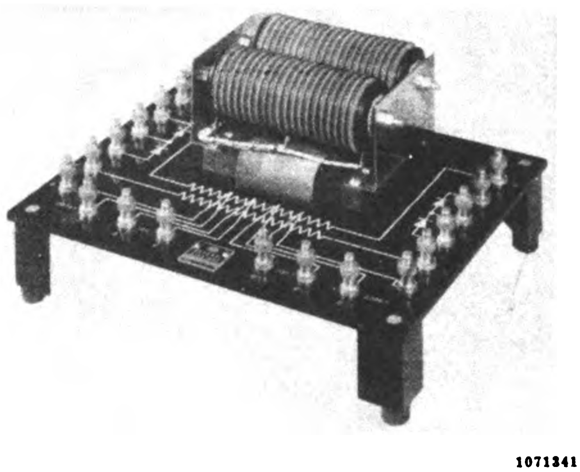


Fig. 11 - Educational Amplifier 60 cycle 100 watt - General Electric Co. - (Not suitable for audio or HF)

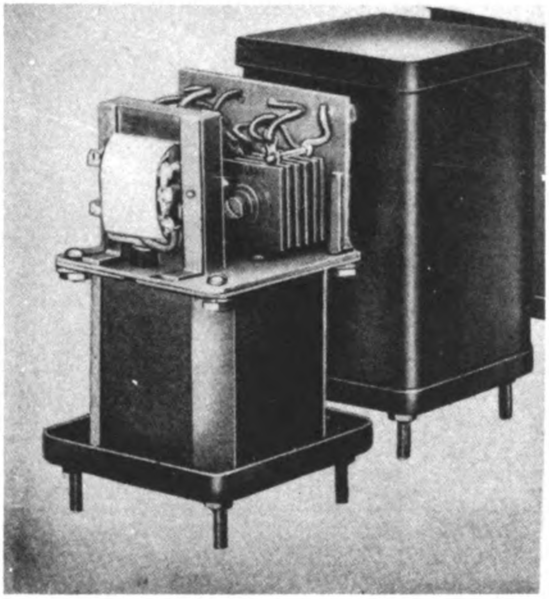


Fig. 12 - 400 cycle 10 Watt.
Mag. Amp. Inc.

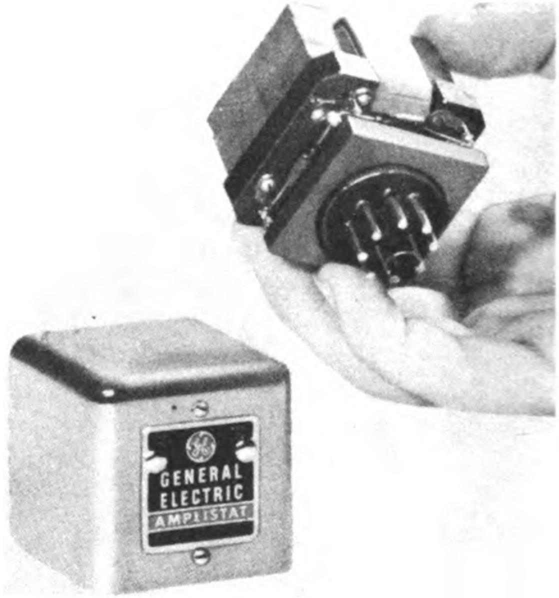


Fig. 13 - 60 cycle 2 Watt
General Electric Co.

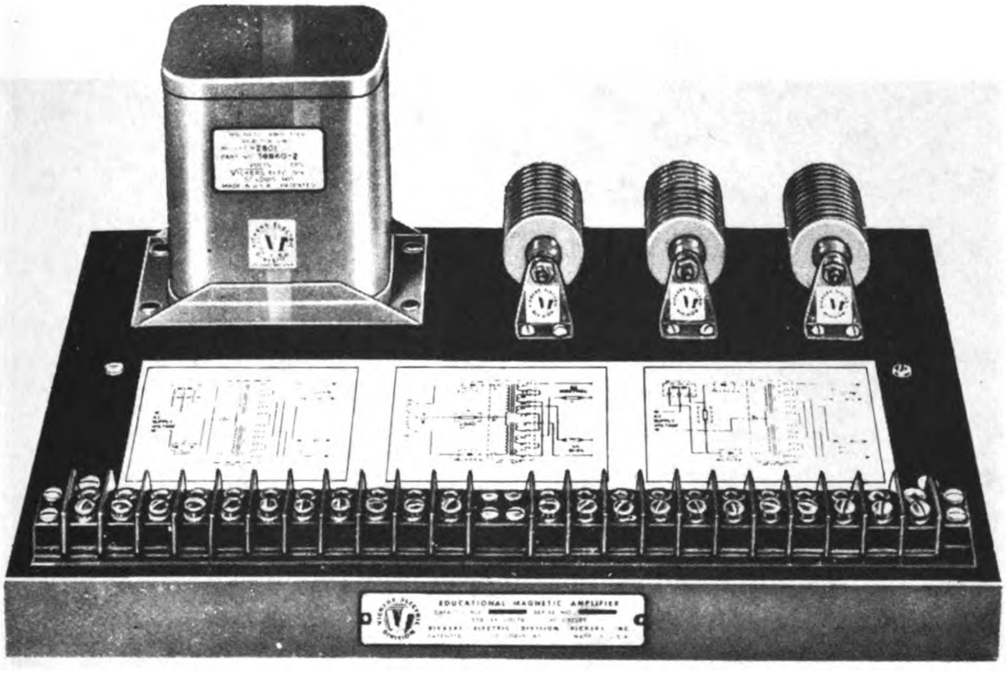


Fig. 14 - Educational Magnetic Amplifier (Vickers Inc.) (Not suitable for audio of HF experiments)

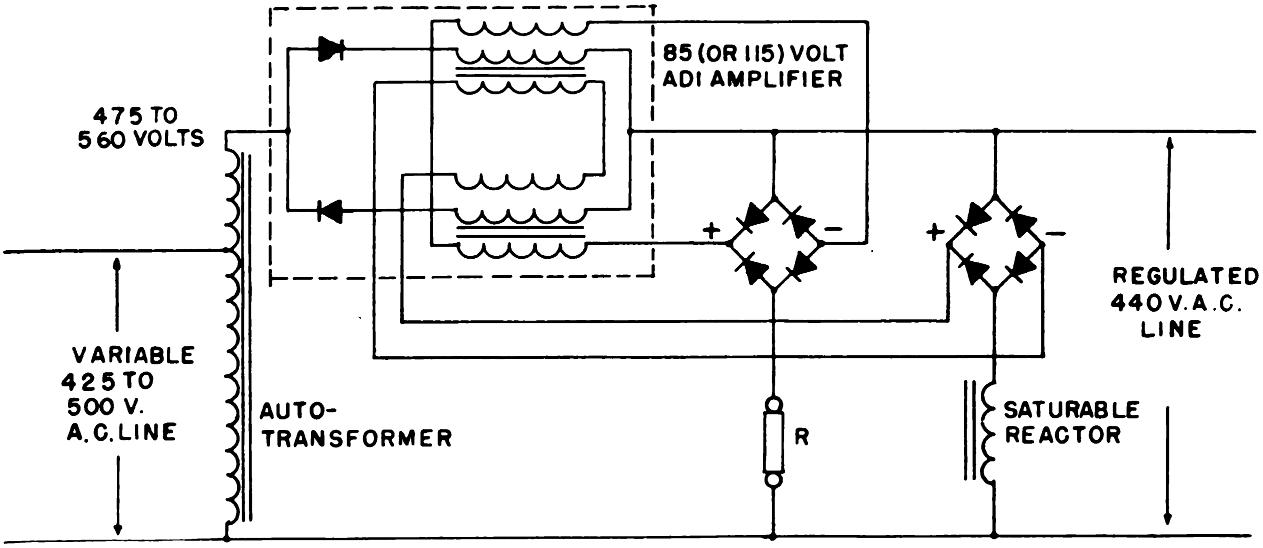


Fig. 15 - Example of one of the various experiments that can be made with the educational amplifier. In the above sketch it is used as a voltage regulator.

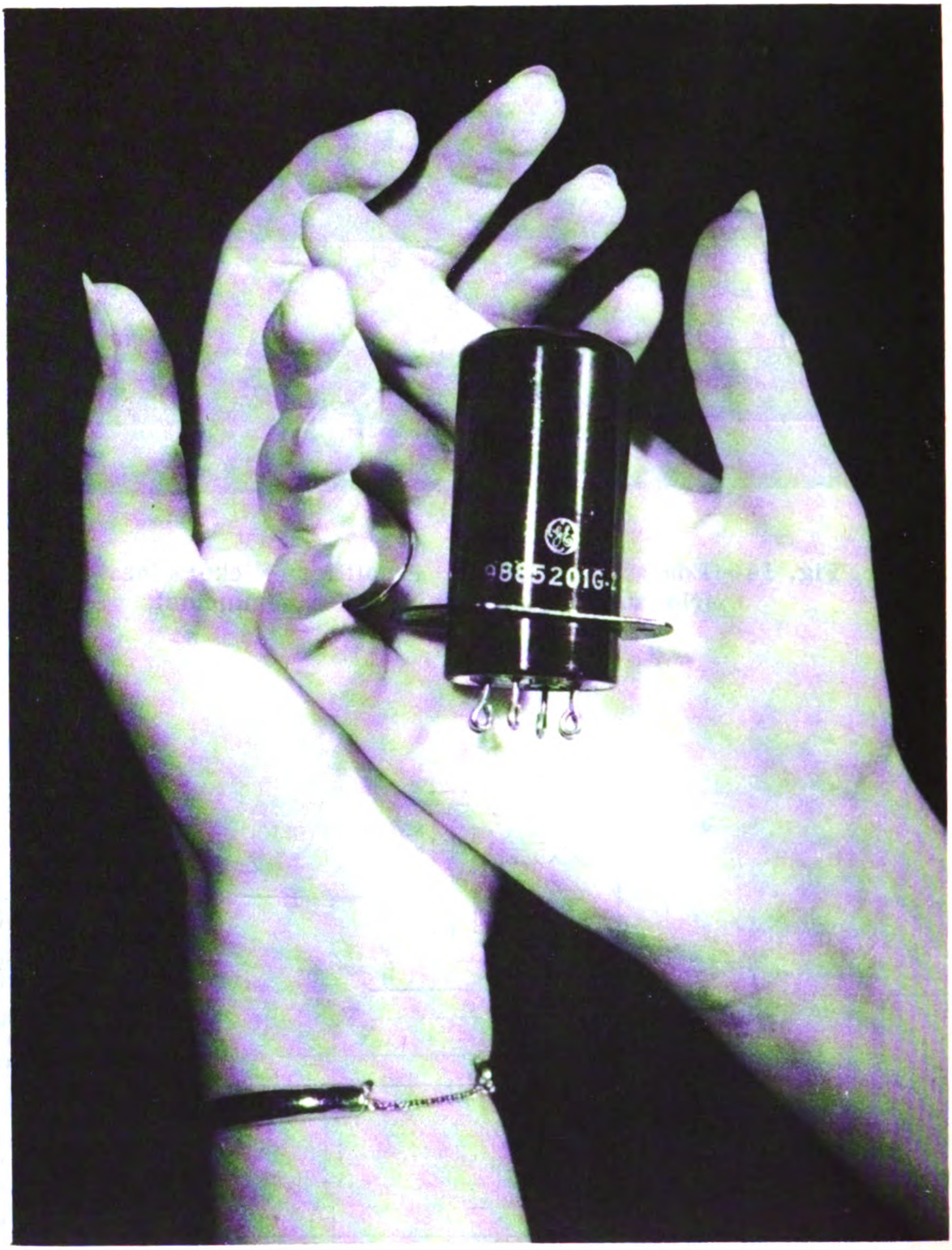


Fig. 16 - Magnetic Amplifier for Jet Engine Thermocouple Unit. General Electric Co.

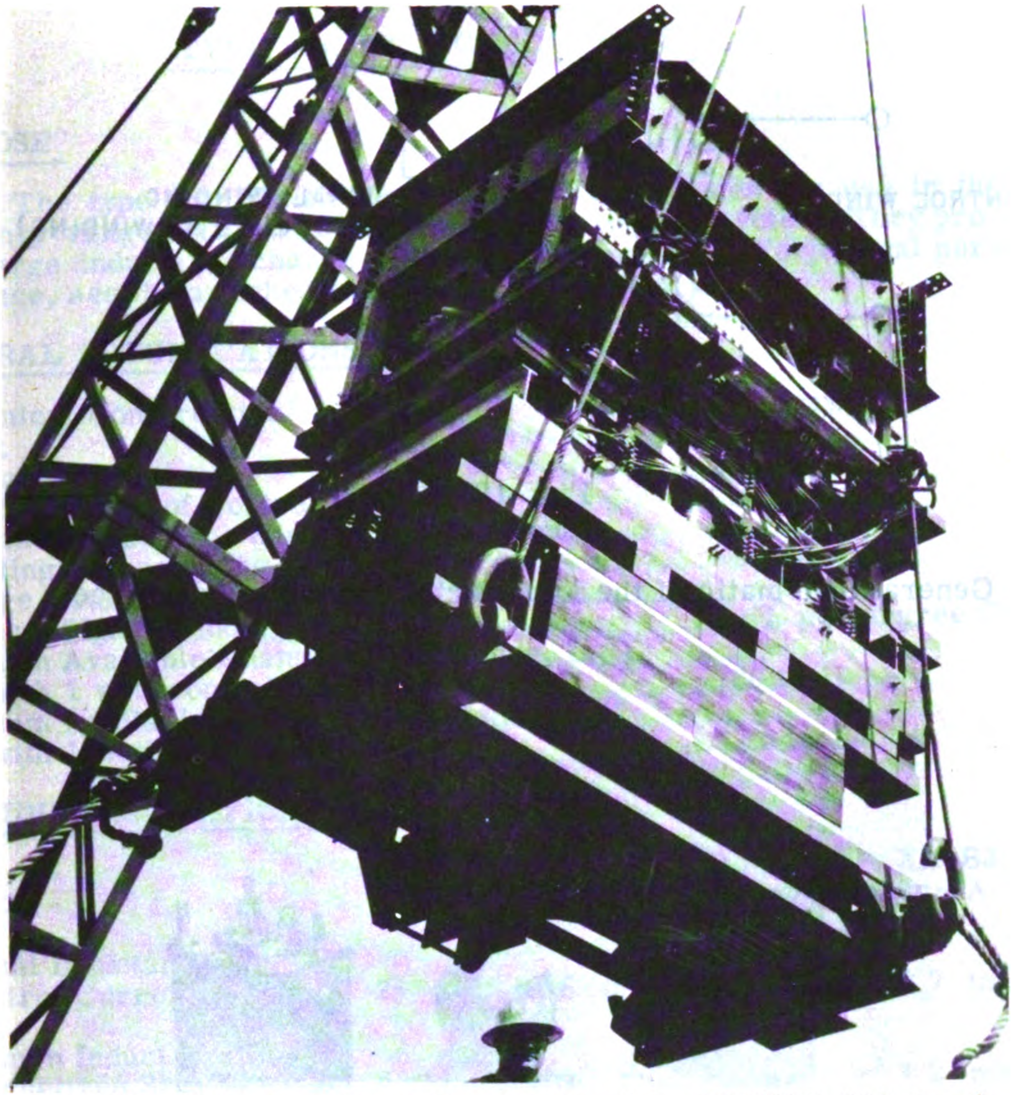


Fig. 17 - Selenium Rectifier designed for HP(175,000 Amp) Magnetic Amp.

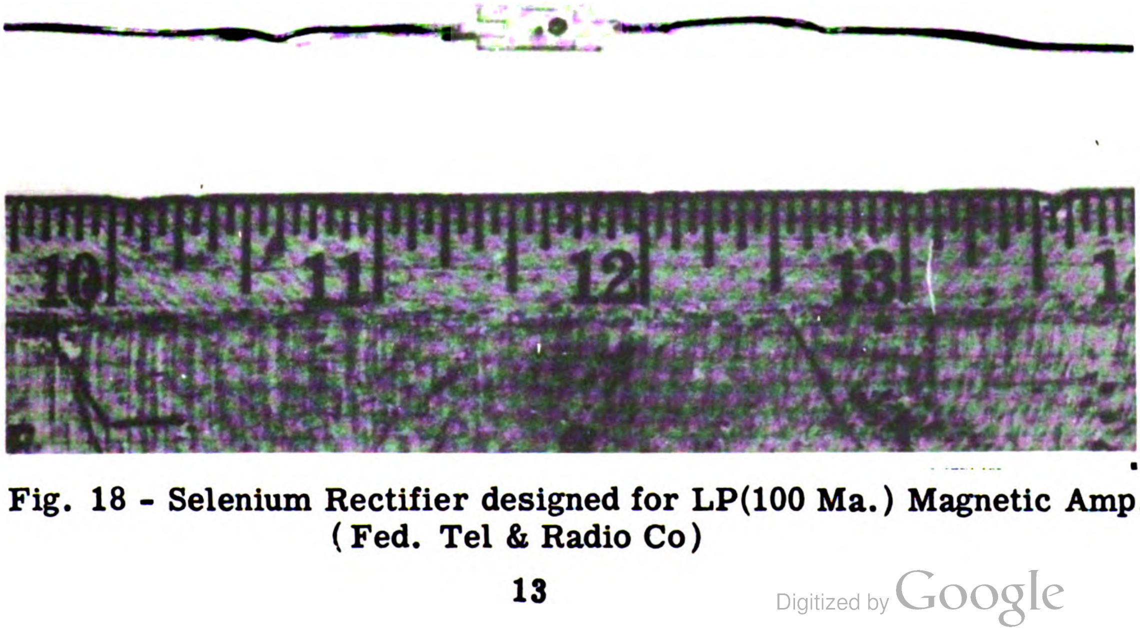


Fig. 18 - Selenium Rectifier designed for LP(100 Ma.) Magnetic Amp. (Fed. Tel & Radio Co)

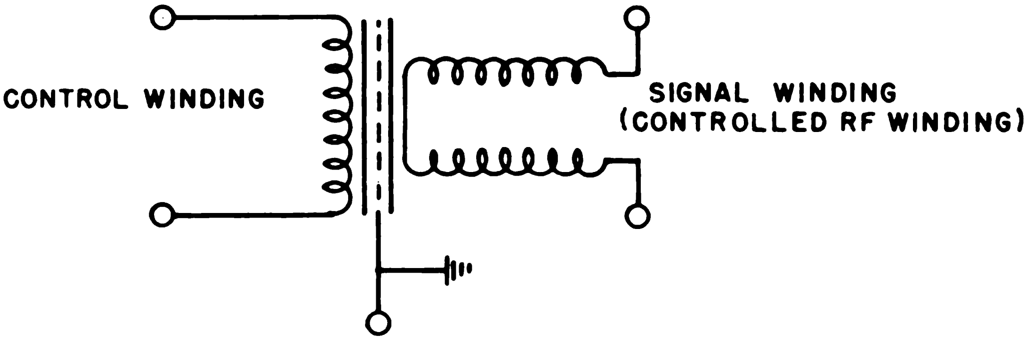


Fig. 19

General Schematic of the Increductor Variable Inductance

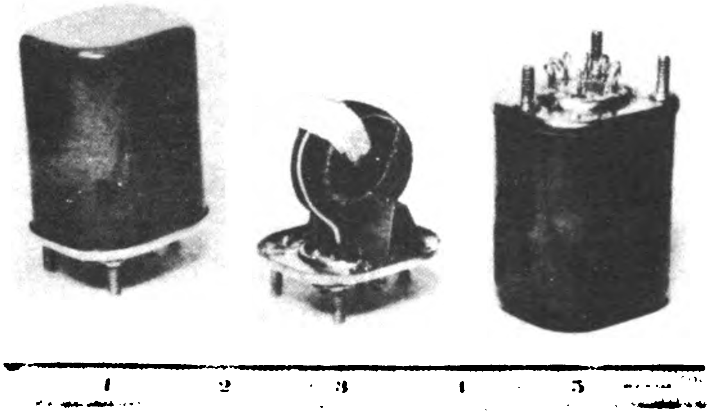


Fig. 20

Type XA-B 3 HF Reactor

C.G.S. Laboratories - Stamford, Connecticut

TYPE XA-B3 INCREDUCTORS*

PURPOSE

The type XA-B3 INCREDUCTORS are intended for use in the frequency range between 100 kilocycles and 10 megacycles. They provide large inductance change with low control power. For typical performance, see the attached characteristics sheets.

GENERAL SPECIFICATIONS:

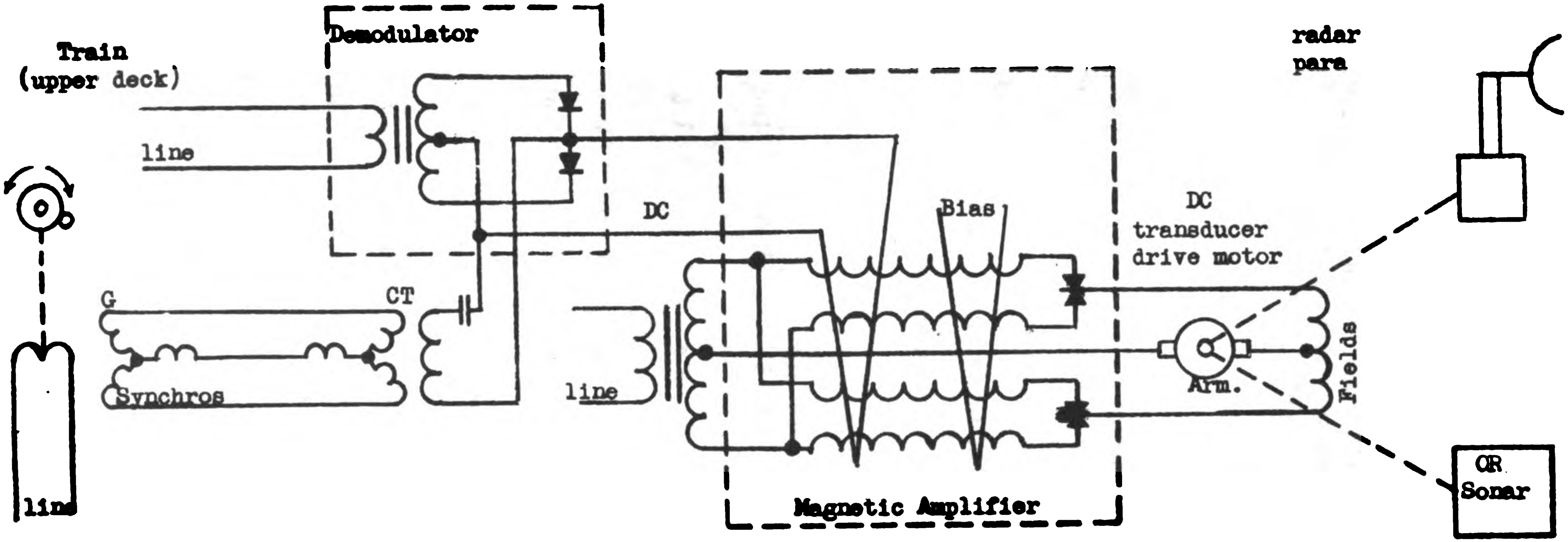
Mechanical Construction	See drawing
Weight	4 ounces
Dissipation Limit	2 watts
D.C. Resistance of Control Winding	250 ohms
Inductance of Control Winding at O Current	6 henrys
Operating Temperature Range	-40 to +65° C.
Average Temperature Coefficient of Inductance, Signal Winding	1.5% per degree C.
Minimum Available Change of Inductance, L_o/L with 1 watt control power	160 to 1
Minimum Available Change of Frequency, f_o/f with 1 watt control power	12.5 to 1

INDIVIDUAL SPECIFICATIONS:

TYPE: MODEL:	XA-B3- 25k-6k	XA-B3- 6k-6k	XA-B3- 15c-6k	XA-B3 7c-6A
Nominal Inductance for O Control Current, L_o	25 mh	6 mh	1.5 mh	0.7 mh
Maximum Inductance, Demagnetized State, L_d	43 mh	10 mh	2.5 mh	1.2 mh
Approximate Recommended Starting Frequency Range	100-300 kc	100-300 kc	200-600 kc	300-900 kc
Approximate Q of Starting Frequency Range	30	30	25	20
Maximum Q within Range	50-70	50-70	40-60	40-60
Current Compensating Factor	7	14	30	45
Maximum Capacity of Signal Winding to Ground	40 uuf	25 uuf	25 uuf	25 uuf

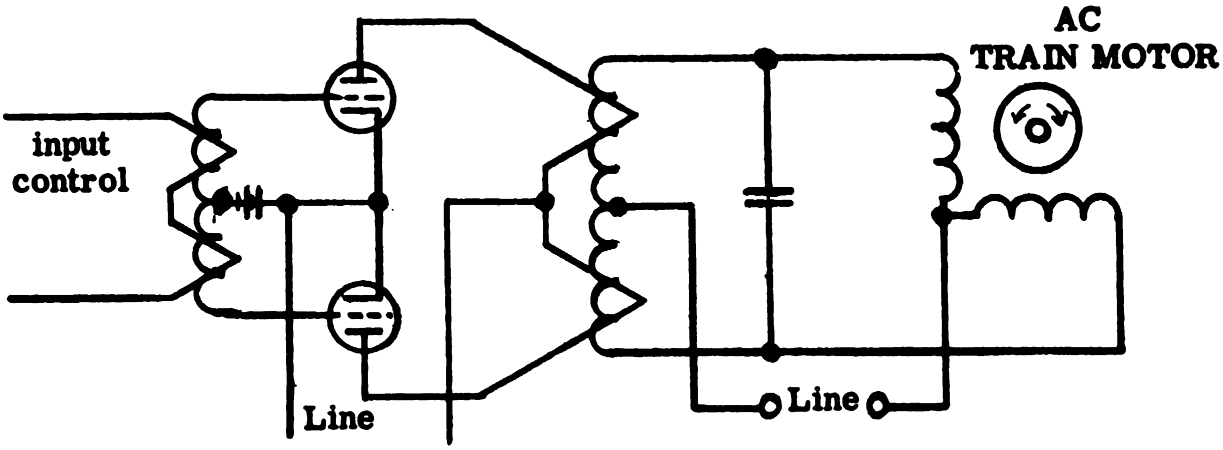
Tolerances: all values plus or minus 15% if not otherwise stated.

*Trademark
Patent Applied For.

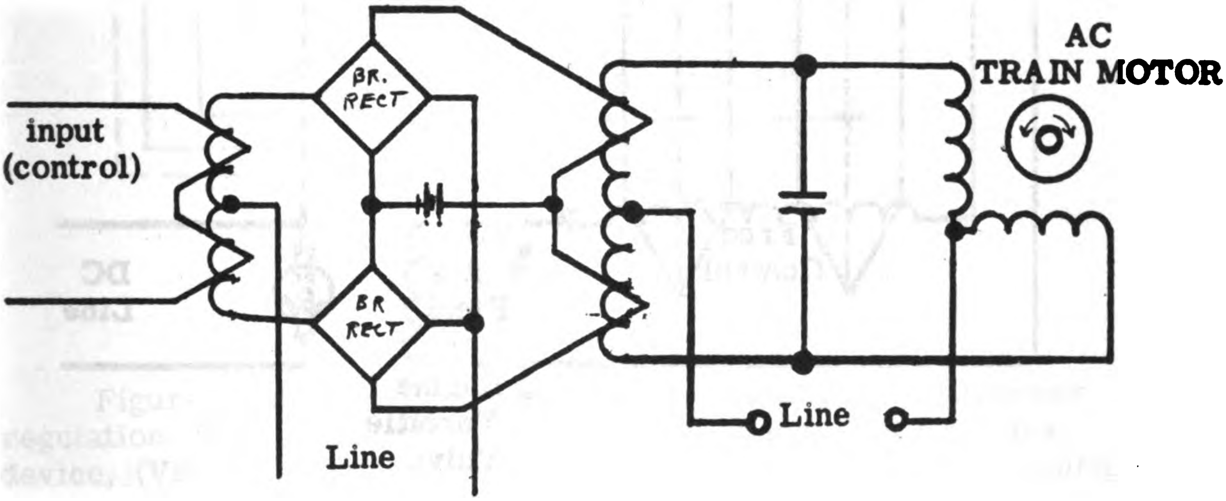


SERVO CONTROL WITH DC SERVOMOTOR

Fig. 21

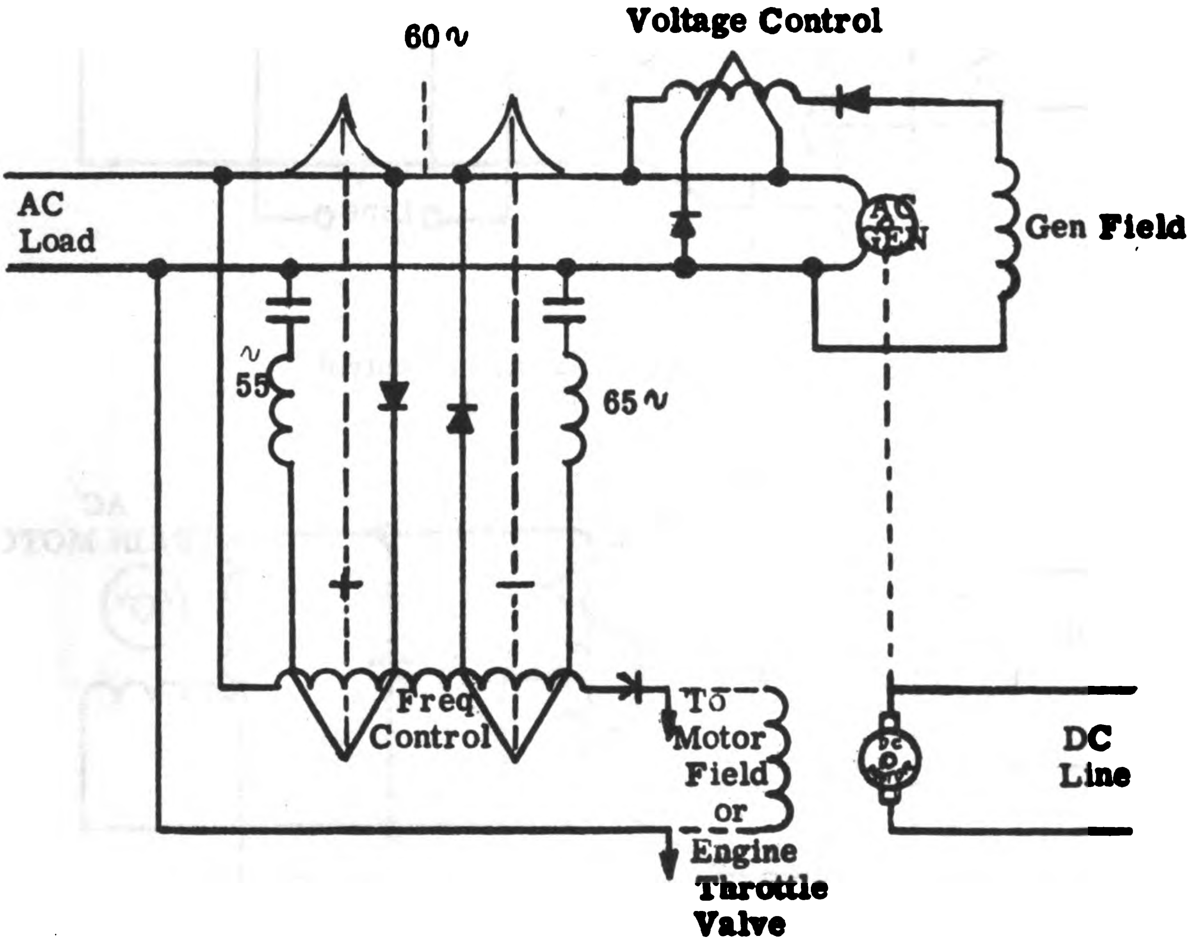


With Thyratron Control
Fig. 22



Magnetic Amp. Conversion
Fig. 23

Figures 22 and 23 contain schematics showing applications to training schemes in servo systems. Fig. 21 is a sketch of a servo system utilizing magnetic amplifiers to replace an amplidyne. Fig. 22 shows a standard thryatron training control drive. Fig. 23 the same circuit modified for magnetic amplification. The thyratron conversion is relatively simple as most of the components designed for this tube will also match the magnetic amplifier. This conversion can almost be simplified to the extent of providing a rectifier adapter to plug into the thyratron tube sockets.



MOTOR-GENERATOR. Voltage & frequency regulated by magnetic amplifier.

Fig. 24

Figure 24 illustrates the principle of applying the magnetic amplifier to frequency and voltage controls of rotating generators. The control coils in the DC drive motor fields are actuated by two tuned circuits resonated at 55 and 65 cycles. The lower frequency coil is wound aiding to increase the DC field current. The reaction of the two currents maintain a constant 60 cycle output.

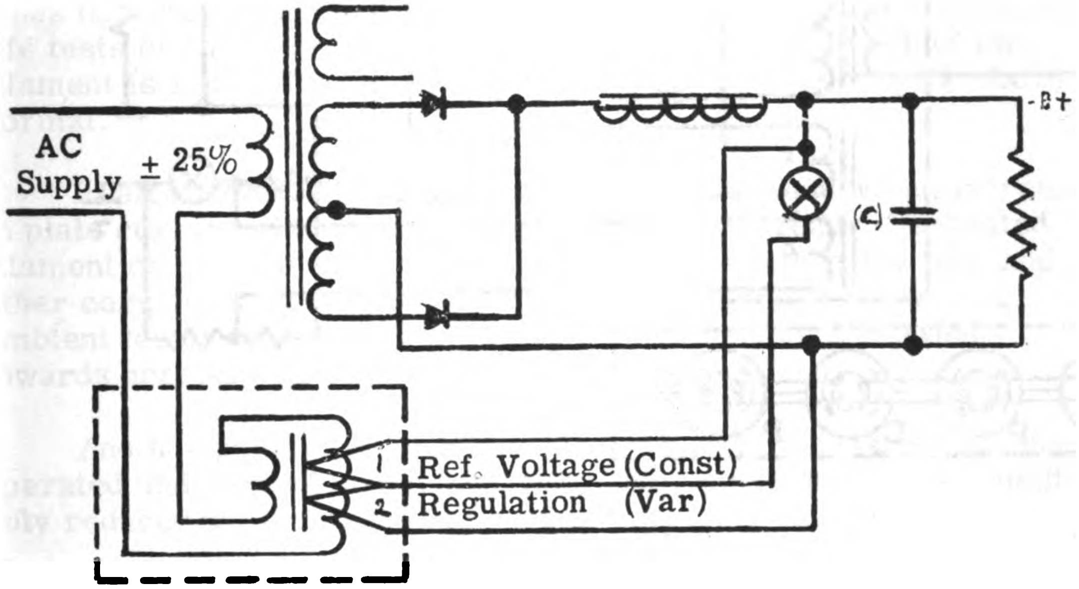


Fig. 25

Figure 25 shows the device applied externally to transformer regulation. The component X across coil #1 indicates a non linear device, (VR tube, Thyrite Etc.) used as a combined reference voltage across coil #1, and a current amplifier for coil #2. Two element non-linear devices are shown for simplicity. When a-c is used as a voltage reference, a small saturable reactor is used for a non-linear device-usually in a bridge connection.

Control coils 1 and 2 may also be applied to choke (L) which would effectively transfer the filter condenser (C) to the other side of the choke upon saturation. The condenser input effect would result in good plate voltage regulation, with Fil. unregulated.

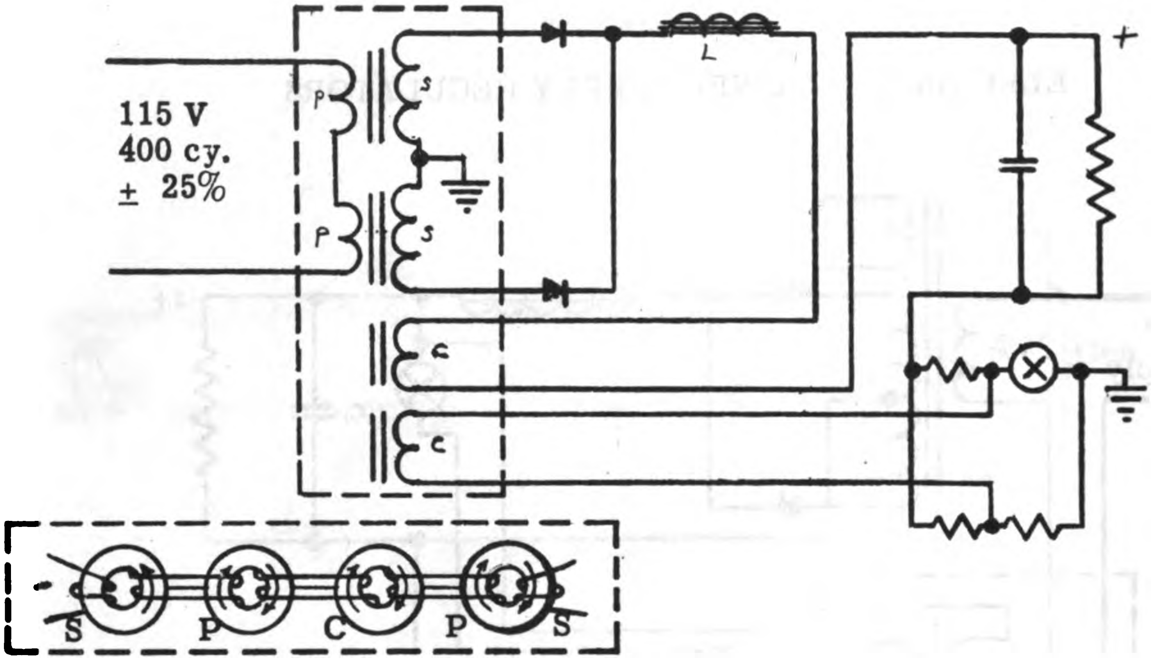


Fig. 26

Figure 26 shows a regulator designed integral with the equipment transformer. This system is used in a special 440 cycle type of aviation radar equipment, and for portable installations where light weight is desired. Insert shows the core arrangement. The above circuits are shown to demonstarte the theory of operation. Other circuits may have superior operating characteristics.

The significance of constant voltage is aprpeciated when it is realized that an estimated 80% of all electronic failures can be directly traced to tube or condenser failures -- this does not include transformer, choke and resistance failures which can usually be traced to overloads occuring during these failures.

"Tubes are listed as the greatest single cause of electronics failures. Cathodes or filaments have an optimum temperature of operation. The incident of failure rises rapidly as temperature is exceeded. Not much data esists on the effect of under temperature operation. It is known that although the latter condition is not as serious as the other, it does shorten tube life. It is desirable to run the heaters at normal ratings from regulated power supplies when long stable service is required of tubes." * Life tests on tubes operated on above normal voltages are not available; however, life tests on incandescent electric lights show that the life of the filament is reduced 50% when operating on a voltage only 7% above normal.**

In electron tubes a rise in line voltage also causes an increase in plate current which adds to the abuse of the already overheated filament or cathode. The additional heat generated by the tube and other components within the equipment compartment causes the ambient temperature to rise which also contributes somewhat towards accelerated equipment failures.

Another point often overlooked is that once the tubes have been operated under accelerated conditions their performance is considerably reduced when returned to normal operating voltages.

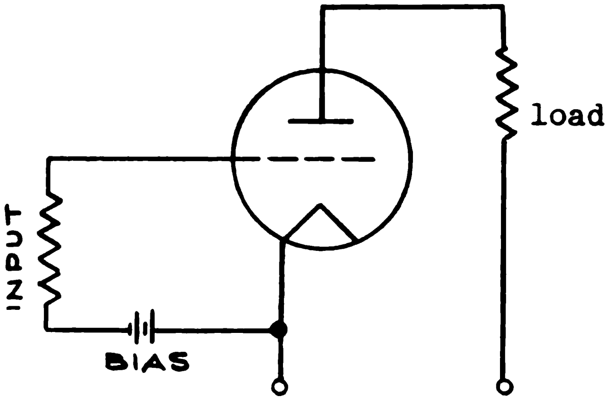
Military equipment is designed to operate at ± 10% of a specified voltage. The service free life however is reduced considerably when operating in the upper voltage range.

Normally the larger naval vessels have excellent voltage regulation. This voltage however is maintained to the trunk lines; the branch lines due to intermittent loads are difficult to regulate. This results in accumulated equipment strains, eventually ending in complete failure.

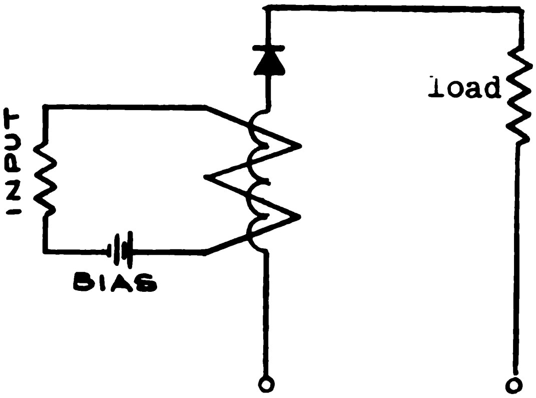
Several manufacturers can supply automatic voltage regulators as components to be inserted between the line and equipment. These are rather large, with low efficiency and are somewhat sensitive to frequency, as most of them operate on the resonance saturation principle. Regulators should be built in the power transformer rather than supplied as a separate component. They should be made mandatory for all equipment where interruptions due to failure may be serious.

* Stamford Research Institute Terminal Report - 1 June 1950

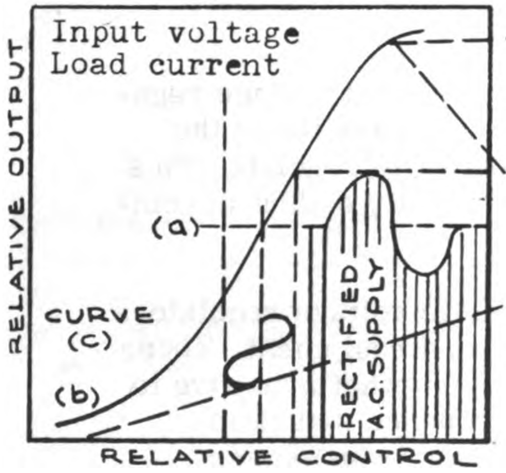
** Chapter 2 NAVSHIPS - 250-660



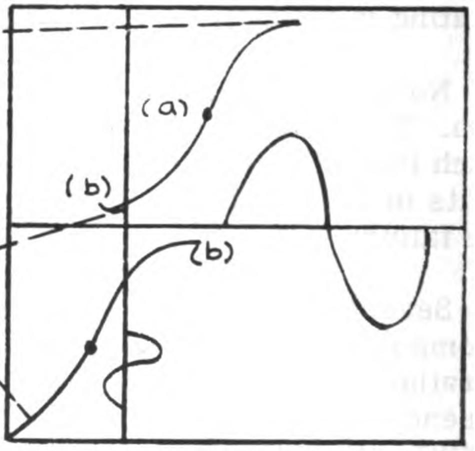
TUBE AMPLIFIER
Fig. 27



MAGNETIC AMPLIFIER
Fig. 28



CLASS "A" SINGLE
Fig. 29



CLASS "B" PUSH PULL
Fig. 30

From an electronics angle, perhaps an analogy between a tube and a magnetic amplifier should be made. Any attempt to analyze the magnetic amplifier in direct relation to a tube requires that certain assumptions be made, as this amplifier differs considerably from the electron tube type. However, since the input saturation control voltage vs load current can be made to follow almost precisely that of a tube, a theoretical analysis can be made on the straight portion of the curve.

Figs. 27 and 28 are sketches of a tube and magnetic amplifier; Fig. 29 is a magnetic saturation vs impedance curve of a typical magnetic amplifier. Since this curve almost duplicates that of certain type tubes, operating characteristics of both can be plotted on the same curve, For a fair comparison the "Plate" supply of both amplifiers must be AC, as a magnetic amplifier will not control DC. If this amplifier is to be used to amplify audio frequencies the supply frequency should be above audibility. Since both amplifiers are single ended, they must be operated as class "A", half way up the slope, as shown in curve (c), point (a).

These amplifiers working as class "A" would not only be inefficient, but provisions would have to be made to separate the carrier from the voice frequencies; consequently they are usually operated as push pull class A/B. With this connection the carrier can be, point (b), biased out, as shown by Fig. 30 . With P/P connection the "plate" supply rectified pulses are also doubled and smoothed out.

Figs. 31 and 32 show basic sketches of more practical push pull amplifiers. Fig. 32 is a single stage amplifier capable of gains up to several thousand. These amplifiers have been constructed with several stages in cascade with power outputs up to 500 watts with excellent linearity up to 7000 cycles.

According to two British investigators (Williams/Noble -IEE, 50-See Bib.), it is possible to amplify control signals of ten to the minus 18 watts at a bandwidth of 10 cps in a special magnetic amplifier having a basic limitation of 4 x 10 to the minus 20 watt due to thermal noise. Barkhausen effects in the same magnetic amplifier are equivalent to a signal input of 10 to the minus 19 watts for a bandwidth of 1 cps. Drift is the major limiting factor in low input applications.

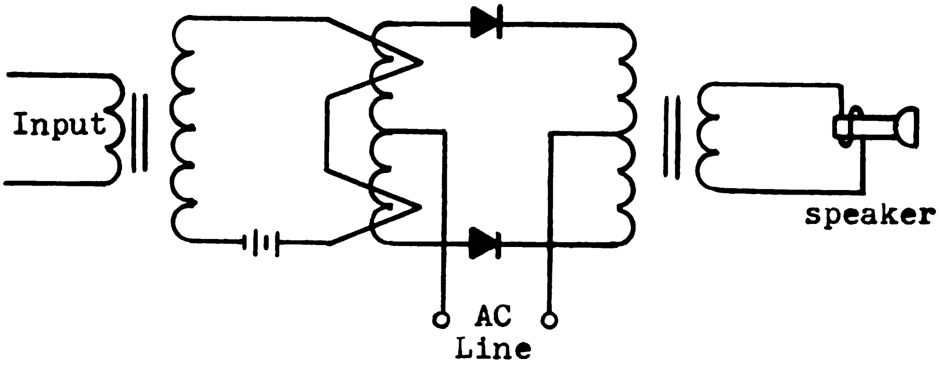


Fig. 31

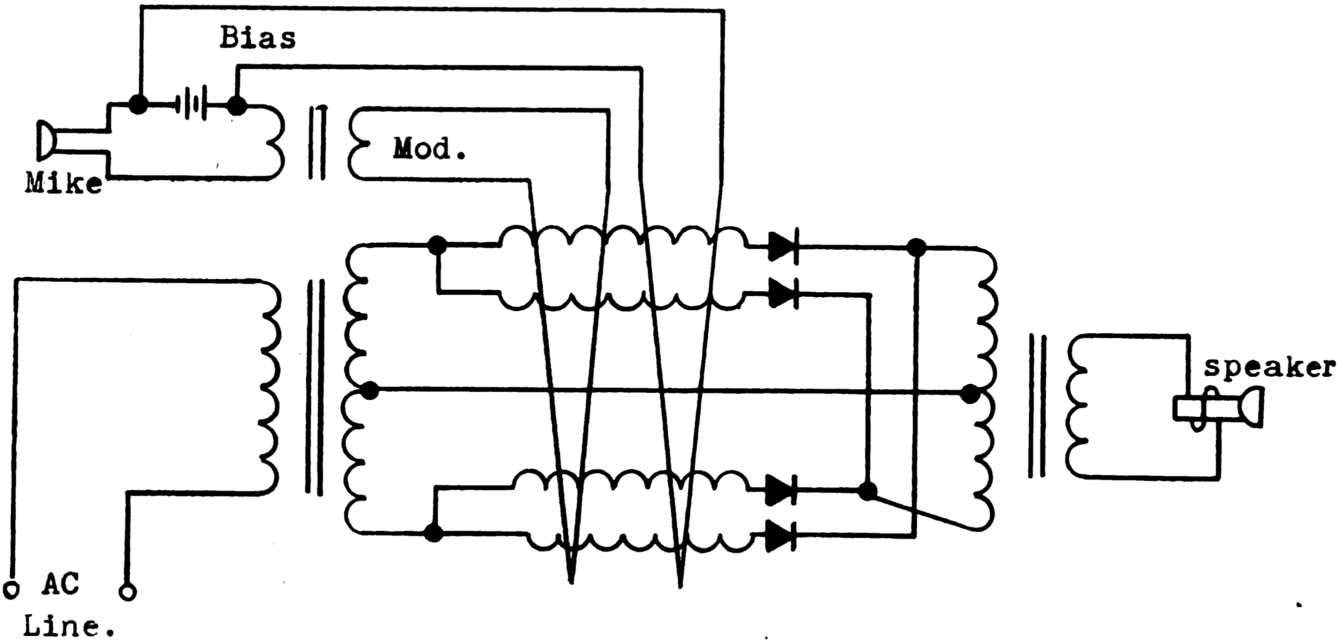


Fig. 32

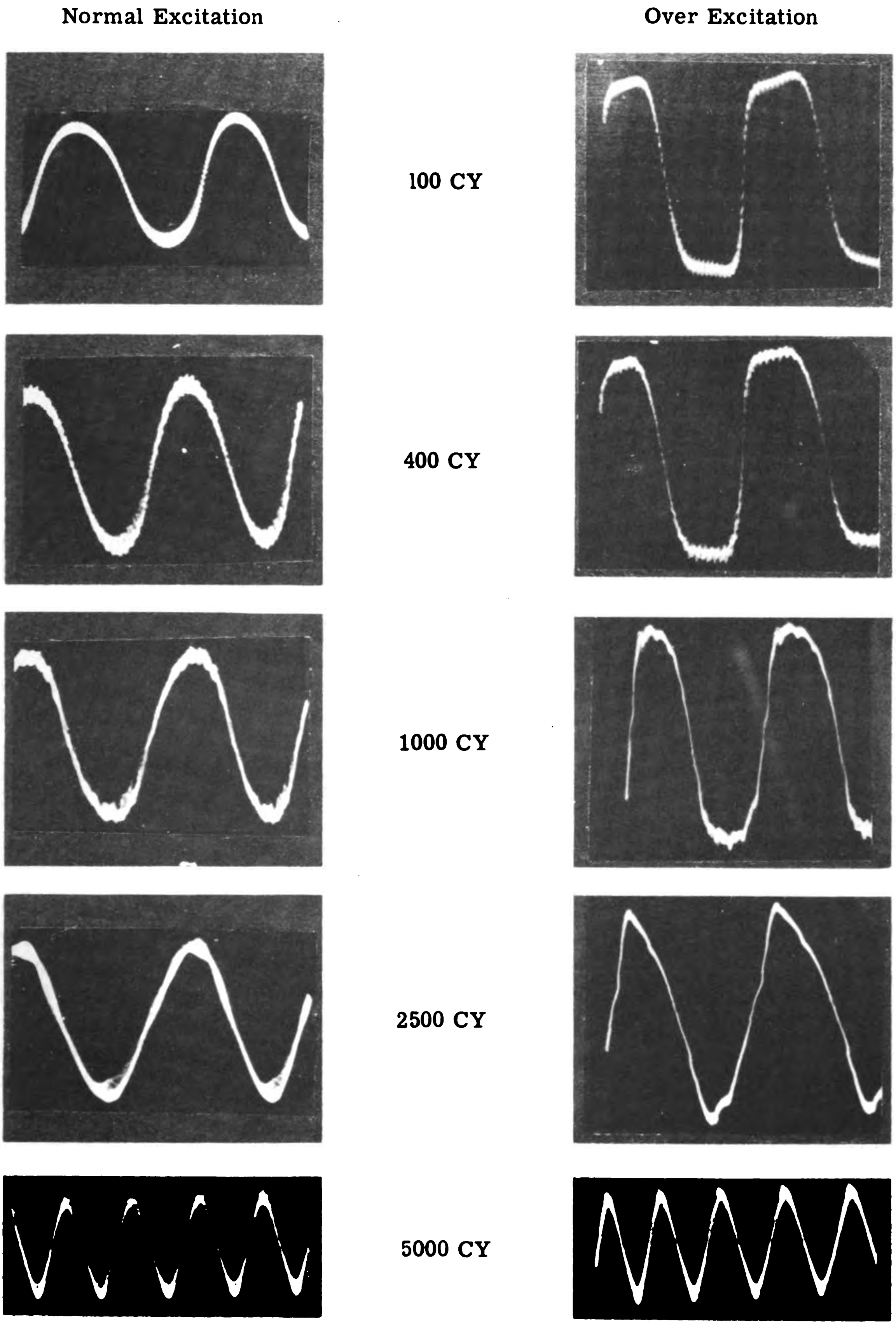


Fig. 33 - Output Oscillograms; 100 Watt Magnetic Amplifier.

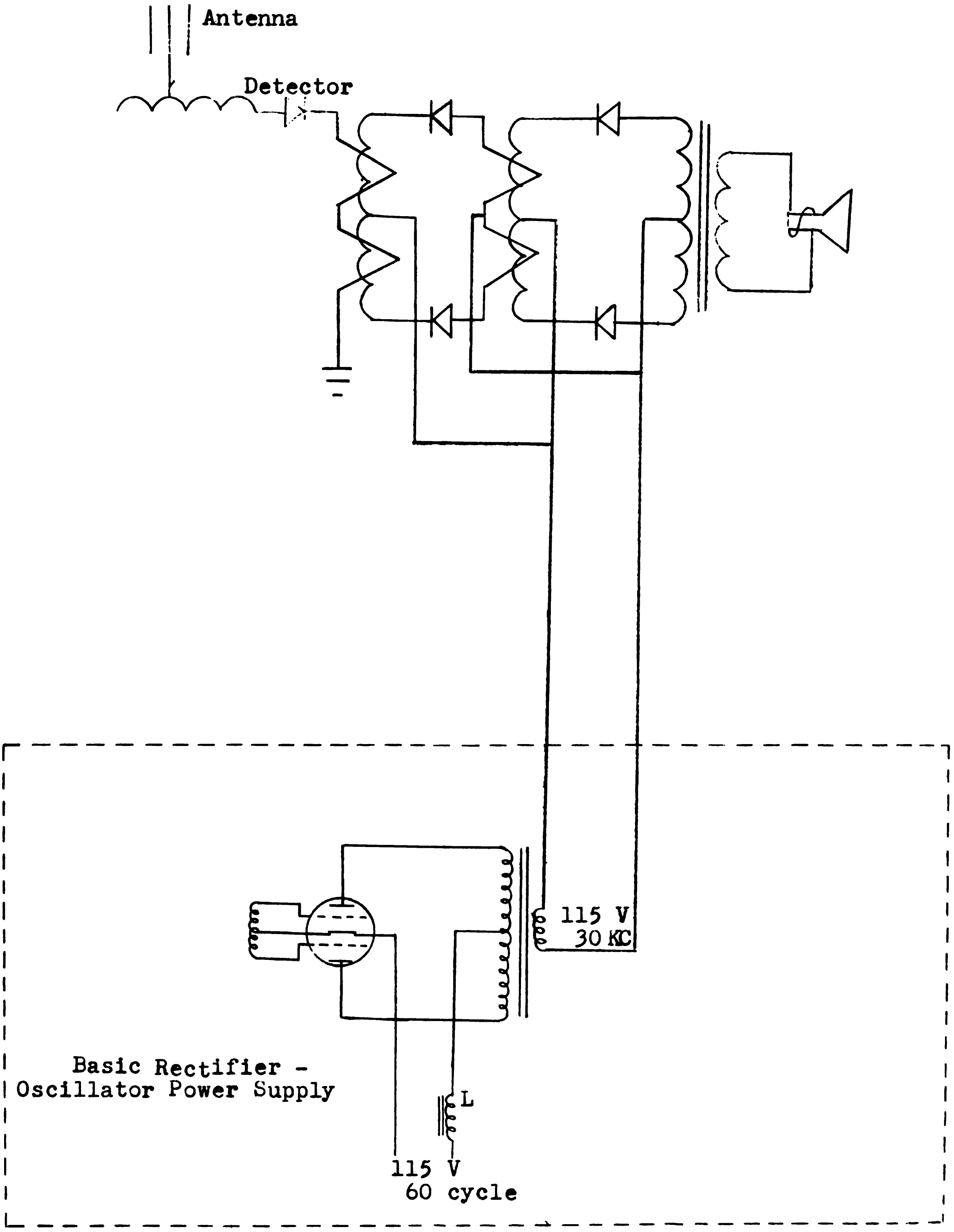


Fig. 34 - Basic Receiver Principles

HIGH FREQUENCY APPLICATIONS

Magnetic Amplifiers are relatively new to electronic engineers, perhaps because until recently, the response time of the device has been too long to be considered for many electronics applications.

Recent developments in core material and application techniques have elevated the device to a more competitive position with electron tubes. Amplifiers now have been developed to respond to frequencies up to the megacycle range.

Circuits for wave shaping, gating, counting, and for pulse generators and pulse amplifiers have been designed to handle pulses up to 500,000 per second.

Magnetic flip flop combinations are also used as frequency discriminators, band pass switches, sharp cut-off filters, and more recently promising results have been obtained towards developing sine wave HF oscillator.

Flip flop combinations are also being developed into square wave, one shot and free running multivibrators. A basic flip flop circuit is shown in Fig. 35

The oscillograph patterns, Fig. 36 indicate that the device can be used for many HF applications heretofore dominated by electron tubes.

One commercial radio firm constructed a complete broadcast receiver using the magnetic amplifier for the RF-IF and audio system, with a germanium crystal transistor for the oscillator; Crystals were used for detectors. A static magnetic converter was used as a frequency multiplier power supply. This broadcast receiver, it is understood, was constructed primarily for publicity purposes to show that a relatively intricate electronic device could be made without the use of electron tubes.

Aviation interests are now considering placing contracts on a loran receiver-indicator completely actuated by magnetic amplifiers except for the scope and oscillator tube. It is planned to design the oscillator with sufficient capacity to act as a combined heterodyne and HF power supply to actuate the magnetic amplifier circuits. This will reduce the present tube complement from 32 to 2 - one of which is the 'picture" tube.

WINDING NUMBER:	1	2	3	4	5
NUMBER OF TURNS:	100	50	50	100	165

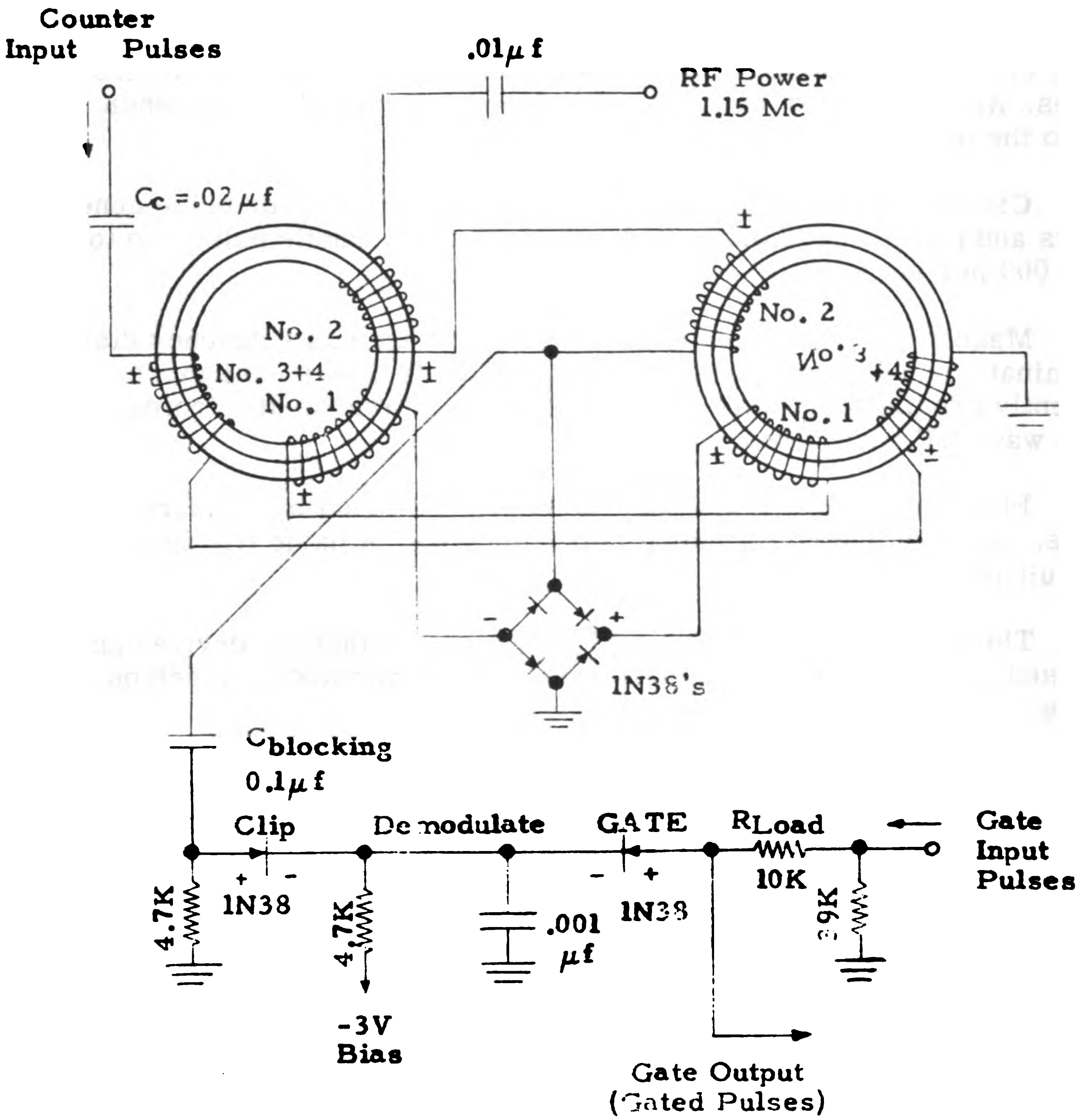


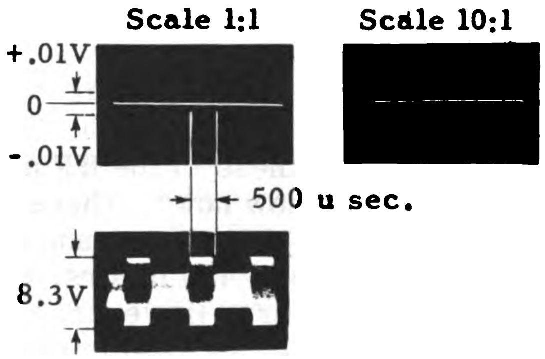
FIGURE 35 - CRYSTAL DIODE PULSE GATE CONTROLLED BY MAGNETIC FLIP FLOP

1. Pulse Repetition Rate = 2000 pps.
(Time between pulses = 500 u sec.)

Input Pulses:

Note: Input Pulses in each case are minimum amplitude required to set Flip Flop. Increased Pulse amplitude is required at higher rates.

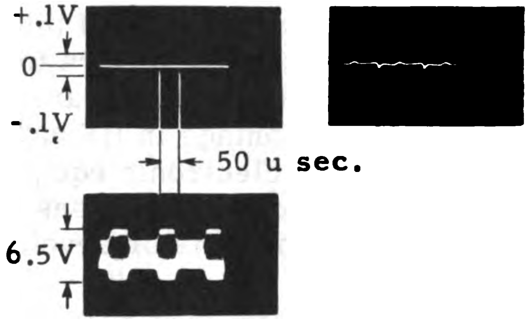
RF Envelope:
(RF = 1.42 Mc.)



2. Pulse Repetition Rate = 20,000 pps.
(Time between pulses = 50 u sec.)

Input Pulses:

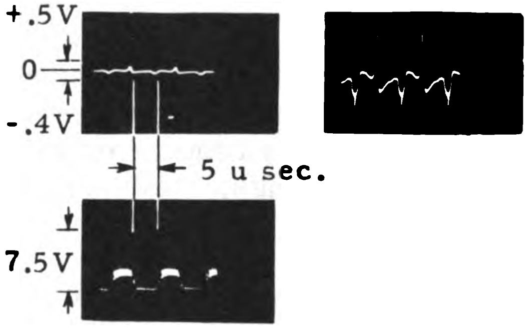
RF Envelope:
(RF = 1.32 Mc.)



3. Pulse Repetion Rate = 200,000 pps.
(Time between pulses = 5 u sec.)

Input Pulses:

RF Envelope:
(RF - 1.4 Mc.)



4. Pulse Repetition Rate = 400,000 pps.
(Time between pulses = 2.5 u sec.)

Input Pulses:

RF Envelope:
(RF = 1.5 Mc.)

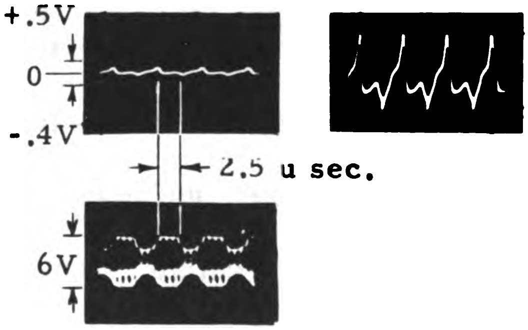


FIGURE 36 - MAGNETIC FLIP FLOP DRIVEN AT HIGH RATES

The weakness in the HF application field is development and application "know how". There are many firms that specialize in magnetic amplifier design and development for electrical machinery such as controls, regulators, servo applications up to audio frequency amplifiers. However, very few of these firms are qualified in HF techniques as used in electronics equipment. The electrical machinery firms probably would take the contracts and subcontract the engineering to the electronic manufacturers.

This has been one of the main factors retarding the development of magnetic amplifiers to HF work in the past. Magnetic amplifier electrical firms are not capable of applying this amplifier to the best advantage in HF applications. Therefore, it appears desirable that electronic equipment manufacturers be given these contracts without restrictions - to either subcontract for the magnetic components or develop the hybrid coils themselves.

Those companies who have been prominent in both the electronics equipment and the magnetic amplifier field should be favored for initial contracts in order to accelerate applications.

Physical and electrical characteristics of the magnetic component will be entriely different after modifications for HF - probably not even recognized by the machinery amplifier firms. HF applications require extremely thin core laminations, anti-capacity windings, etc. that are not found in present production units.

Following are some of the core characteristics desirable for HF applications.

1. The core must be easily saturable.
2. Eddy current effects must be at a minimum.
3. Hysteresis losses must be low.
4. The physical mass of the core must be small.
5. The effective retentivity of the core must be low.

The oscillograph patterns of Fig. 36 were made from the output of Fig. 35 which contained a core made of 4-79 molybdenum permalloy tape 1/8 mil thick and 3/32 inch wide. The core had an inside diameter of 1/4 inch and weighed 20 milligrams; the ration of inductance from zero to maximum saturation was 4:1 - (80 to 20 uh). The RF anode power supply consisted of a single tube oscillator supplying each magnetic stage with about 20 MA at 20 volts. The excitation voltage of course varied with signal input.

The above information together with the oscillograph pattern, Fig. 36,and Fig. 35 was obtained from a BuShips contract report as furnished by Engineering Research Associates, Inc., St Paul on saturable-core reactors as digital computer elements. This contract was completed 17 June 1949.

This research indicates that conventional rolled core material can be used for frequencies up to possibly a megacycle with fair efficiency. Beyond this range preliminary investigations indicate that composite iron or related magnetic material such as powdered iron or ferrites may be superior.

Powdered iron cores similar to those used in conventional RF tube circuitry are not suitable for efficient magnetic amplification.

In powdered iron cores, the desirable high volume resistivity is achieved by bonding fine metal particles in some form of organic binder. This reduces the permeability and leaves the core full of air gaps which is undesirable from the standpoint of efficient saturation required for magnetic amplifiers.

The deficiencies of the powdered iron core, however, can be ignored in certain circuitry in connection with magnetic amplification such as impedance matching coils and other specialized applications where amplification is less important. In one instance these cores were used in coils where a high "Q" was important for selectivity which could not be achieved with the other material.

Magnetic ferrites show interesting properties as magnetic core material; consiting only of metallic oxides, this material has a high volume resistivity and high permeability, but low losses, making for reduction in size and weight in FH circuitry.

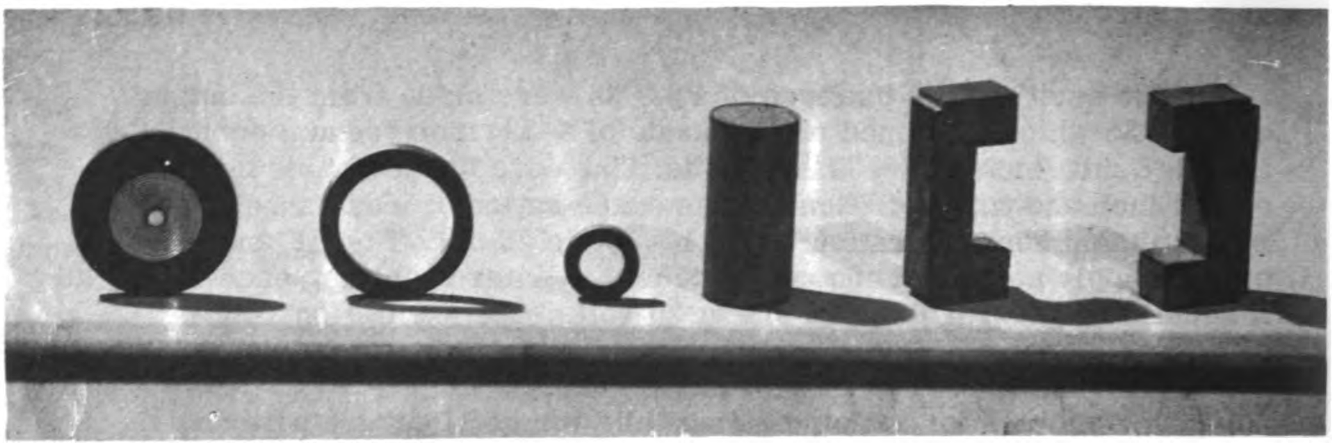
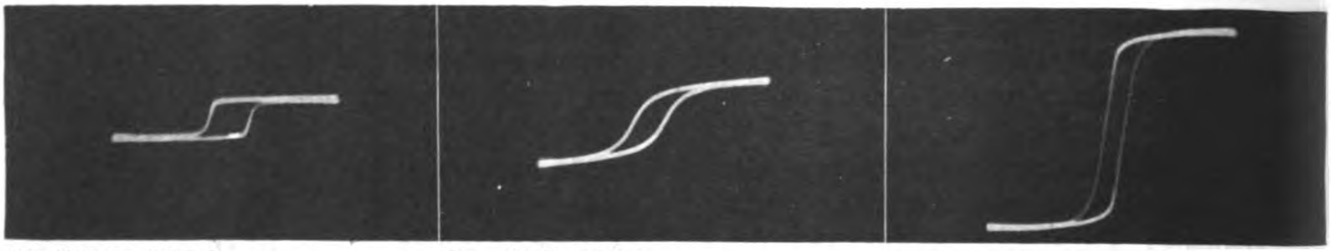
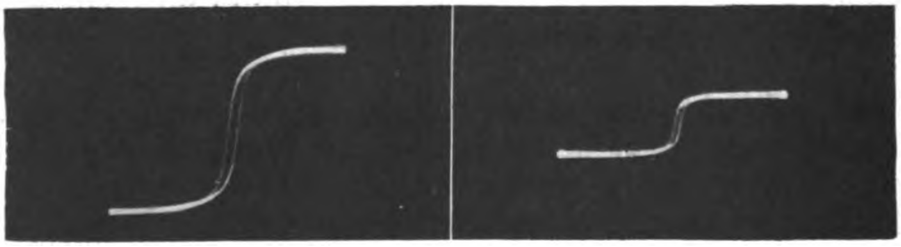


Figure 37 - Ferramic parts in the form of a disk, toroids, slug and C-shaped transformer cores were pressed. The rod, which is 20in. long and 3/8 in. diam, was extruded. A spiral inductor was printed directly onto the ferrite disk, illustrating the high specific resistance of this material.



FERRAMIC 34, TYPE A   FERRAMIC 90, TYPE B   FERRAMIC 156, TYPE C



FERRAMIC 146, TYPE D   FERRAMIC 141, TYPE E

Figure 38 - Oscillogram traces of hysteresis loops of five types of ferrites.

Ferrites, unlike powdered iron, contain no metallic particles but consist only of metal oxides; any organic material that would act as air gaps would be fired out during the 2300° processing temperature. It is this structure which is responsible for the main advantage of ferrites over powdered metal core materials in HF circuits.

Ferrites, with their natural high specific resistance do not have to be powdered and suspended. Therefore, the permeability is not diluted, resulting in a maximum permeability of around 1000 compared to 100 in powdered iron rings.

Ferrites have found applications in horizontal sweep transformers of television sets, RF high voltage power supplies - deflection yokes for TV receivers, tuning stugs for RF coils, core material for FM oscillators, high "Q" core assemblies, etc. Ferrites, incidentally, are also being used as delay lines for pulsed video and super sonic signals and as transducers at sonic and super sonic frequencies. Fig. 37 shows ferramic core forms, Fig. 38 hysteresis loops. Fig. 39 shows a comparison between a magnetic and a tube amplifier - These are single stage RF computer components designed by Transducer Corp.

Very little definite information has been obtained on special HF core material - whether ferrites or some other composition is best suited for high frequency magnetic amplifier cores has not been determined.

Most of the above material on ferrites was furnished by General Ceramics & Steatite Corp. which was supported in part by U. S. Signal Corps contract No. W-36-039.

If sufficient emphasis is put on these applications of the magnetic amplifier the program need not be a long term one. The prospects of much greater reliability and simplification of electronic equipment which appear to be immediately available should not be ignored.

In adidtion, recent developments in transistors and dielectric amplifiers offer possibilities of using a combination of all three devices to eliminate all tubes except those used for visual displays.

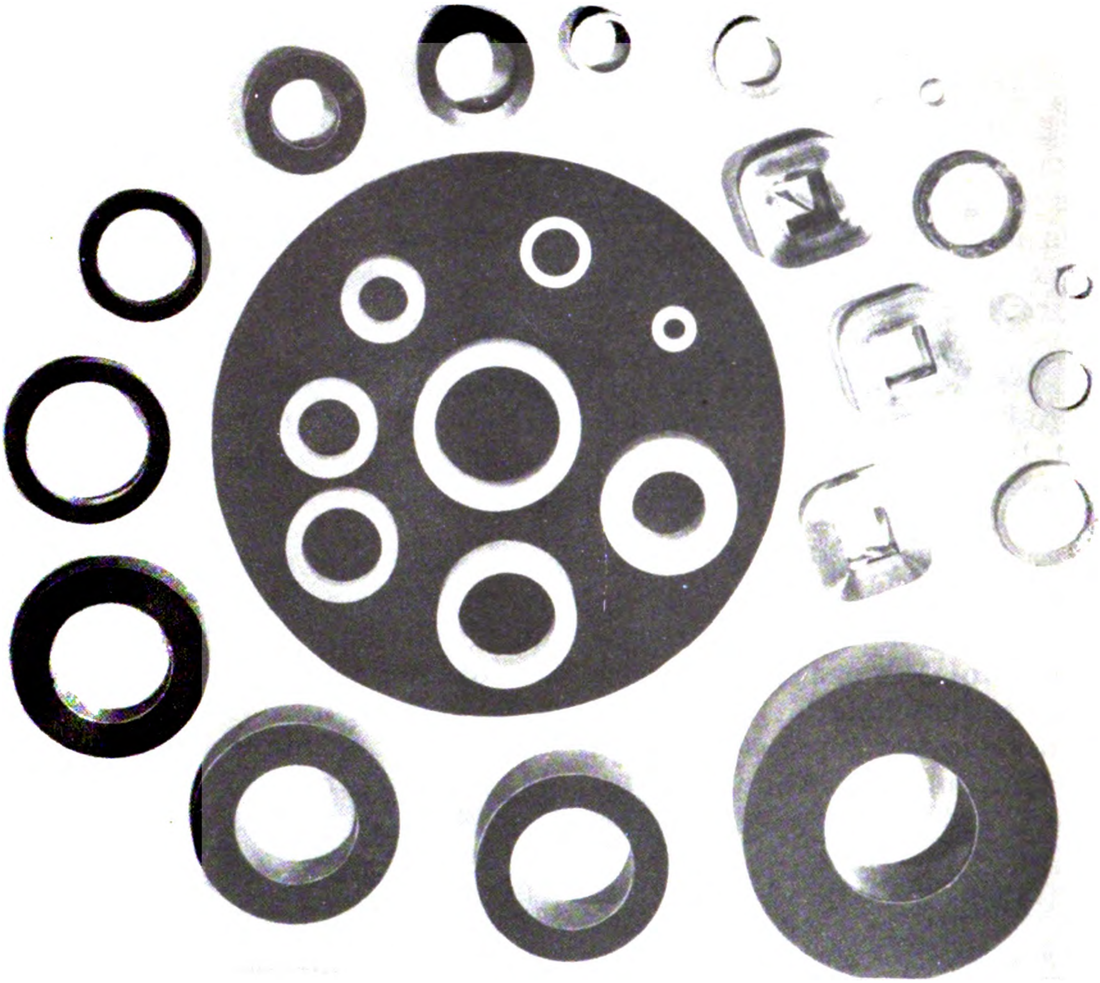


Figure 39 - Misc. tape wound cores - Arnold Eng. Co.

Figure 40 - HF Cores - Magnetics Inc., Butler, Pa.

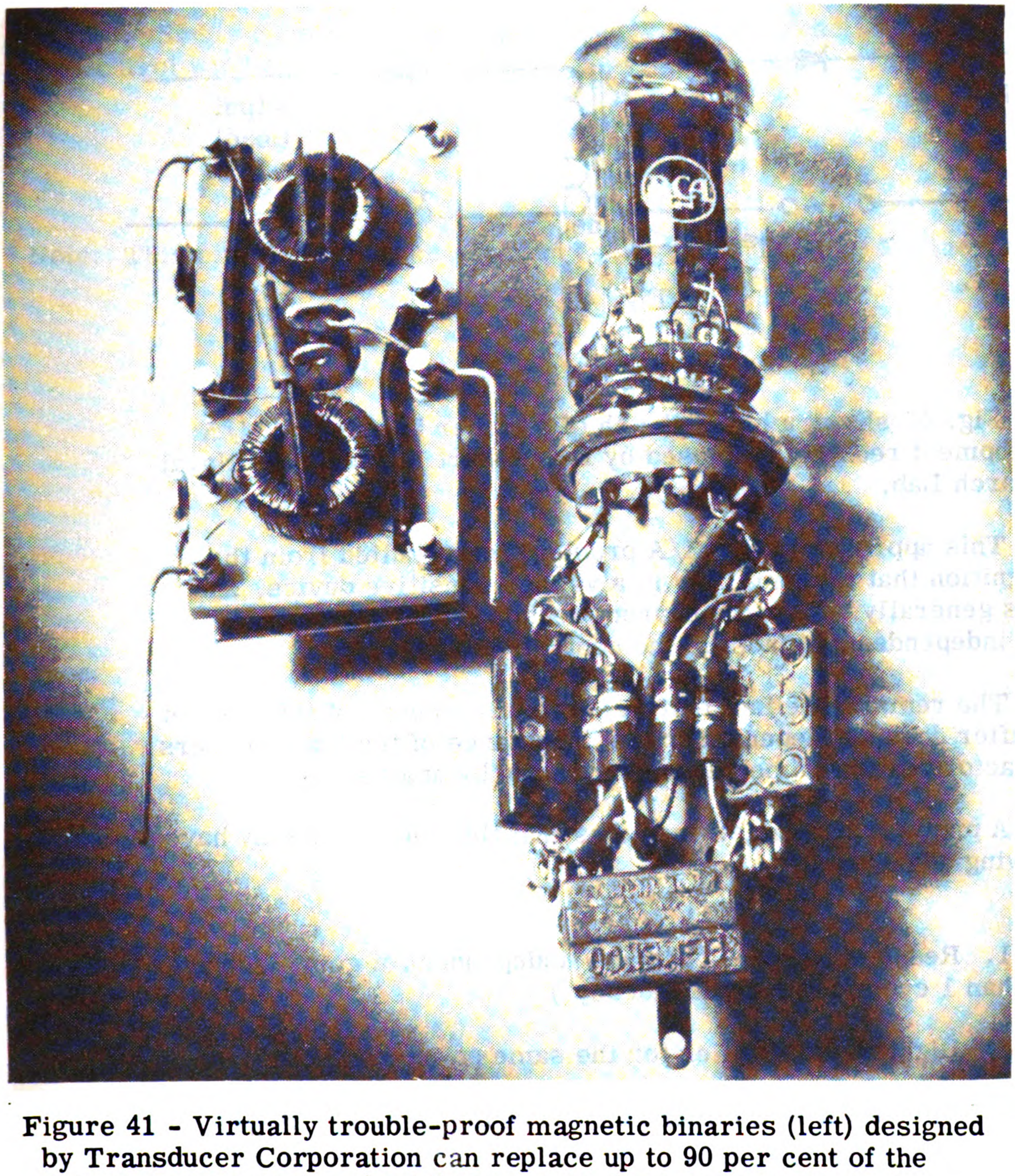


Figure 41 - Virtually trouble-proof magnetic binaries (left) designed by Transducer Corporation can replace up to 90 per cent of the delicate vacuum tubes (right) in certain digital computers.

NEW DEVELOPMENT

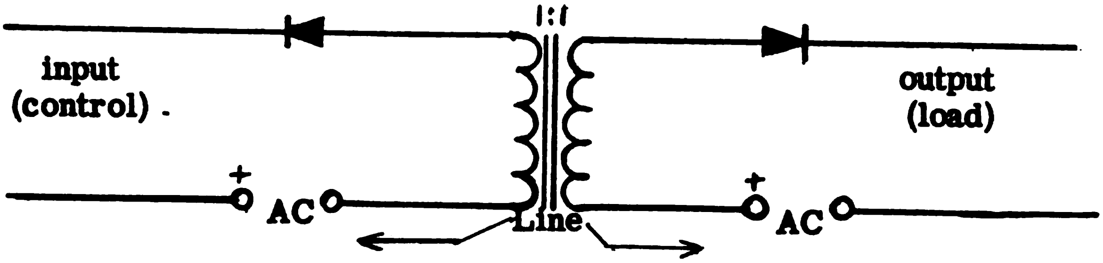


Fig. 42.

Fig. 42 shows a basic sketch of a rather interesting M/A development recently disclosed by Dr. Robert A. Ramey of Naval Research Lab.

This approach to the M/A problem has resulted from the recognition that the amplifier is a voltage sensitive device, and not as generally believed a current sensitive device. The only truly independent variable is the control voltage.

The remarkable fact that the time of response of this series amplifier does not depend upon the inductance of the transformers as reactors seems to be adequately shown by analysis.

A preliminary review indicates that this amplifier may have the following advantages:

1. Response time is constant, independent of gain. (Always less than 1 cycle of supply frequency.)

2. Lighter and smaller for the same power output.

3. The output is a linear function of the control voltage.

4. Greater power sensitivity; the control source need not supply power to the amplifier control. Power is absorbed instead..

5. Relatively independent of variations in supply voltages.

6. Single core reactors may be used with little reaction into the control winding.

Note: This circuit has not as yet been evaluated by BuShips Engineers.

GENERAL COMMENTS

The emphasis on magnetic amplifiers should be directed towards definite applications in electronic equipment to increase reliability where this can be accomplished without an overall reduction in operational performance.

The unreliability of current electronic equipment is a very serious problem and evidence exists that the electron tube is the largest single factor in equipment failures. The following quotations are of interest regarding the reliability of electronic equipment, in particular the electron tube.

"For military services two factors are of extreme importance (1) an overwhelming problem of equipment maintenance; and (2) an almost insuperable demand on production facilities of the manufacturers in the event of total mobilization, making replacement of components and (or) equipment due to failures a serious problem. Any preventative measures taken now will result in high dividends during an emergency and for years to come."*

"The developing complexity of electronic circuits, such as radars and sonars, make the tube problem a serious one. Data gathered for this study indicate that in equipments using components which meet military specifications or best commercial grades, the electron tube accounts for more than 50% of circuit failures.

In one case an analysis on service calls over an eight week period showed that 72% of the breakdowns were due to tube failures.

In Commercial Aircraft electronic equipment it is reported that 70% of equipment failures are due to tube faults, even thought the tubes are ruggedized units whose average life has been improved by a factor of more than 24 over the standard commercial types.

With an increasing number of tubes used, and greater reliability of other components, the reliability of the equipment becomes more and more the reliability of the electron tube itself."**

In other fields where reliability is paramount, the M/A is already being used or rapidly adapted to electrical machinery.

Submarine engineers were among the first to visualize the importance of this device from a reliability standpoint. Practically everything that moves in a submarine is being studied with a view to possible actuation by static controls. Relays subject to failure due to dust or sticking contacts are being replaced with magnetic amplifiers. Motor-generators and other components supplying delicate electrical instruments in these vessels have been regulated by M/A for some time; kits are also being provided to modify starter-regulators on electrical equipment on older type submarines to the more dependable static type control.

Aviation engineers are considering M/A controls in many locations previously dominated by relay mechanisms. In these applications, the unreliability and fire hazard of a relay have always been a consideration.

Atomic energy engineers are also specifying M/A controls in many critical positions where a breakdown could cause astronomical losses in time and material once a reduction process has been started. In one application, single units capable of controlling currents up to 150,000 amperes are being installed.

The application of magnetic amplifiers to RF and other high speed wave forming circuitry are not considered as feasible of accomplishment within the immediate future. These applications will require long range developments.

The applications based on the uses outlined in this article have had considerable development both in this country and abroad and therefore should be considered first for special applications.

* Office of Naval Research - Monthly Research Report 1/50
** Stanford Research Institute Terminal Report 11/50

APPLICATIONS

(The following list of magnetic amplifier applications was originally submitted as an enclosure to a Bureau of Ships, Electronic Design & Development memorandum dated 11 October 1950)

1. "Applications of the Magnetic Amplifier" are listed as follows:

a. AMPLIFIERS - AC or DC for current voltage and power. Example: Low level DC applications: Thermocouple and photo cell amplifier to directly operate motors and controllers. Amplification gains of several million can be realized without the use of electronic tubes but with rather long time constants. This is an excellent DC Amplifier. This amplifier is not subject to drift difficulties often encountered in electron tube installations.

b. REGULATORS - (most common use) control of voltage, current and frequency of industrial power installations, ship main propulsion and auxiliary units, aircraft automotive electrical equipment, line to line voltage regulators independent of frequency. (Regulating applications have been thoroughly proven and should be considered for all auxiliary generators supplying power to electronic equipment - a large portion of electronic equipment failure can be attributed to poorly regulated power supplies.)

c. RELAYS - Locking including normally closed, open or frequency sensitive relays. (The substitution of these units for mechanical relays should be considered for equipment used in the tropics, where contact and mechanical difficulties are encountered due to humidity and fungus, as they contain no contacts and moving parts and can be completely sealed.)

d. SATURABLE REACTOR - Lighting control, variable impedance, etc. Single units are currently used to control up to 50,000 KVA.

e. MOTOR STARTER, ELECTRICAL WELDING AND AUTOMATIC BATTERY CHARGING CONTROL - The effectiveness and sensitivity of regulating controls are considerably increased by the addition of a non-linear device such as a THYRITE or glow tube which can be connected to effectively amplify the error or act as a reference source themselves.

f. CURRENT LIMITING REACTORS - Limiting power currents during short circuits. Limiting armature currents during slow motion or static conditions in follow-up motors.

g. SERVO SYSTEMS - Complete, utilizing magnetic amplifiers as regulators, converters, computers, and as a complete replacement for thyratron and a rotary magnetic amplifier (amplidyne) system, at less cost and weight.

h. INSTRUMENT AMPLIFIERS - Remote control, etc.

i. SYNCHRONIZER - For automatic pulse and frequency control.

j. DIFFERENTIATION SYSTEMS - For course plotters and predictors (Example: Direct integration from DECCA, RAYDIST, LORAC and RADUK-II phase comparison meters to graphic course plotters) constant speed controls for Surveying, Wire Drag, Mine Laying, Convoys, etc.

k. AUTOMATIC STABILIZERS & PILOTS - For submarine and aircraft. (AC power supply systems for aircrafts are well established making saturable reactor control extremely attractive.)

l. IMPULSE STORING AND MEMORY DEVICES -

m. TIMERS - Timing pulse generator for radar and loran equipment - Wave shaping, etc. (currently produced with frequency range between 25 cycles and 1 MC.)

n. ELECTRICAL COMPUTERS - Add - subtract - multiply - divide - differentiate - or integrate electrical quantities.

o. CONVERTERS - DC to AC - AC to DC. - Another method of converting DC to AC at both 60 and 400 cycles for the elcetronic equipment on auxiliary vessels equipped with DC main generators. Rotary converters and motor generators on any vessel have always been a maintenance problem. This application is still under development.

p. OSCILLATORS - Within limited frequency range.

q. PHASE SHIFTERS - Reactance control to 1/4 cycle - currently used as phase shifters in grid control of mercury arc rectifiers - and pulse delay matching circuits in radar equipment.

r. FUEL PUMP REACTOR DRIVES - (In location where relay starting and controls contacts sparks could cause an explosion).

s. MODULATORS - Voice frequency modulators and RF carrier trigger circuits. Frequency shift keyers, etc.

t. FREQUENCY MULTIPLIERS AND REDUCERS - Including telephone tone and rigging circuits up to RF. In one type of frequency multiplier a direct current flux is added to cause operation of the unit at the most efficient point for the generation of the desired harmonic. Another static type recently developed to convert 60 cycles to 420 has an efficiency of 60% with a considerable reduction in weight over comparable rotating equipment.

u. SEISMOGRAPH AND MAGNETOMETER AMPLIFIERS - tide gauge, anticipator, audio gain sequence circuits. - Drift difficulties often encountered in these applications are usually reduced when this device is substituted for tube amplifiers.

v. MULTIVIBRATORS - One shot and free running square wave generators.

w. SWEEP GENERATOR - Trigger and pulse forming circuits for Radar and Loran equipment.

x. COUNTER AND DIVIDERS - For loran, shoran and radar indicators.

y. MINE AND SUBMARINE DETECTORS -

z. FIELD CONTROL FOR MAGNETIC FLUID CLUTCHES & MAGNETIC POWDER BRAKES - One manufacturer has replaced the regular DC charging generator on an experimental bus with a 400 cycle AC unit. The generator voltage is magnetic amplifier controlled to plus or minus 2% from idling to full speed. Magnetic amplifiers are then used to obtain optimum battery charging rates, and as remote controls for the powdered iron brakes, clutch and miscellaneous auxiliary equipment, including RF ignition systems.

ADVANTAGES

2. The Magnetic Amplifier has several advantages for electronics which are as follows:

a. They contain no moving parts. Maintenance of the unit without rectifiers is comparable to that of a conventional transformer. With rectifiers the life is governed by the type of rectifiers used - conventional radar germanium crystal rectifiers are used in the low powered units - dry disc in the larger units. These rectifiers are rated at 60,000 hours for normal operational demands.

b. RUGGEDNESS - Shock resistance equivalent to that of a transformer of similar size.

c. STABILITY - Less affected by variations in power supply voltage fluctuations in that there is no cathode emission change with filament temperature, (in low input and HF applications constant anode voltages are important). Unbalanced effects in balanced circuits due to cathode emission changes are practically eliminated because of the inherent stability of a rectifier compared to a hot cathode.

d. OVERLOADING - A Magnetic Amplifier can carry overloads equal to an equivalent transformer.

e. ENVIRONMENTAL - Can be hermetically sealed and inconspicuously built in as part of the equipment. Normally requires little ventilation and can be installed in compartments with combustible material.

f. HIGH GAIN - Power gain per stage is comparable to that of a vacuum tube stage. They can be cascaded almost to any power gain. The efficiency is also greater.

g. CIRCUIT ISOLATION - The inputs and outputs are electrically isolated.

h. SAFETY - Can be safely operated in enclosed areas where starting relays and control contact sparks could cause an explosion.

i. ADAPTABILITY - These amplifiers can be built with special shaped cores for mosaic installations in confined spaces. Amplifier gains can be changed simply by adjusting the DC fields. Gain control leads are less affected by stray RF pickup noises often encountered with high resistance high voltage components necessary in equivalent electron tube circuits. Separate low impedance gain windings may be added to the core if isolation is required; (permanent magnets with adjustable air gaps, may in certain applications be used to set fixed gain). Separate windings may also be used to introduce feed back, either positive or negative to obtain increased amplification or degeneration to improve the frequency response. In addition to the above, separate windings have been added to superimpose independently varying signals in either phase relation or amplitude or both for specific purposes.

j. These amplifiers are also excellent devices to use in conjunction with electron tubes for many applications. Tube controlled core saturation can be applied to many existing electron tube installations with a resultant increase in stability operating range and overload protection.

k. READINESS- They require no warm-up time. Example - Gun control units would not have to be kept continuously energized for instant use.

DISADVANTAGES

3. Although this amplifier has advantages as given in paragraph 2 it also has disadvantages and these are listed below:

a. TIME CONSTANT - In general, the time constant is long compared to that of vacuum tubes and short compared to electro mechanical devices. Current servo production units have a lag of one cycle of exciting frequency. Pulse trigger circuits are being designed with lags of less than one microsecond with a HF Power source. Actually, it may be possible with modern materials and techniques to obtain time constants in most cases, comparable with those of vacuum tube circuits, especially in similar applications.

b. IMPEDANCE RANGE - The impedance of a Magnetic Amplifier cannot be increased to infinity or decreased to zero - reflected impedances, therefore must be considered. With full output (core saturated) the output impedance is reduced almost to the DC resistance of the core windings and (if used) rectifiers. Inputs may be designed with an impedance of a fraction of an ohm to a megohm or more.

c. AGING - If feedback units requiring rectifiers are used the life of the rectifier is the age determining factor. Modern dry type rectifiers, conservatively operated have a life expectancy many times that of a vacuum tube, and will stand considerably greater overload surges, and should not, once installed, require service or maintenance during a service life of at least five years. (The log book of the German Cruiser "PRINZ EUGEN" shows that not one of the various types of Magnetic Amplifier used on that vessel for gun stabilizers and servos, required servicing for a period of ten years).

d. FREQUENCY LIMIT - The upper frequency limit of a magnetic amplifier appears at the present stage of development to be about a half million cycles. It is assumed, without further investigation, that this limit occurs due to eddy currents within the core, or winding capacity effects or both. Response of pulse repetition rates up to 400,000 per second have been obtained with time constants of one microsecond, using 3 MC as excitation frequency.

e. CAPACITY - The capacity of the series saturated amplifiers currently produced are limited to around 10 kilowatt due to the size of the rectifiers. Shunt compound units have been built with capacities up to 50,000 KW. Theoretically there is no upper limit to power handling capacity of these amplifiers, likewise there is practically no lower limit; magnetic amplifiers are capable of amplifying signals too weak to penetrate the emission shot noises of a vacuum tube.

1. Size: In many low powered applications the magnetic amplifier may be larger and heavier than competitive units. This is especially true in the 60 cycle components - The size of the core is almost inversely related to frequency. For a given size the 400 cycle amplifiers would have about five times the capacity of its 60 cycle counterpart. The linearity and response time is also improved almost directly in proportion to frequency. High speed replacement units for vacuum tubes, however, indicate that they may be much smaller and lighter than equivalent vacuum tube circuits.

2. COST:. Initially, until mass production is established, these amplifiers will be more expensive than the components they replace. This is due not only to the necessity of absorbing part of the research cost in the first production units, but also to allow protection to cover any possible engineering problems that may develop in special applications. Indications are that once mass production is established magnetic amplifiers can compete in cost not only with electron tube components but with the cheaper electromechanical devices as well.

The uses indicated in the above list are but a few of the many applications. Not all of the magnetic amplifier applications mentioned are commercially available, as some are still in the experimental stage. Basic research on magneto-strictive magnetic amplifiers, oscillators and power units utilizing composite cores of nickel, iron, cobalt, in bridge circuits with permanent magnets for fractional saturation bias levels are now being studied for special applications.

Magnetic amplifiers should not be considered as a substitute for all tubes and relays in control and regulating circuits. Each application should be weighed and balanced against competitive installations. In certain installations, these amplifiers may actually be larger, heavier and less suited than other means. A magnetic amplifier should be considered only if its advantages outweigh its disadvantages when compared with competitive means.

Magnetic amplifiers should be considered for applications within their limitations for many types of equipments now using vacuum tubes relays, rheostats, circuit breakers, meters, certain rotating devices, self-synchronous transmitters, receivers, etc. The reduction of vacuum tubes alone, by any device, is a consideration, when it is realized that the electronic equipment on a single battleship today requires over 7,500 tubes and the number is rapidly increasing. Aircraft Carriers require up to 13,000 tubes excluding equipment installed in planes and in specialized computers. Storage space requirements for three times this number of spares is also a consideration.

The substitution of magnetic amplifiers for all mechanical regulating devices used on auxiliary power units supplying electronics equipment should be made mandatory, limited only to availability. These are relatively simple applications, and should be the first to be considered.

Lieutenant Commander A. M. Vincent, USN, Code 815B, has been temporarily assigned to act as liaison officer between Electronics Design and Development Division, Naval research facilities and manufacturers, primarily to expedite special applications in design. It has been found that due to the limited research in subject matter, a lag of at least a year is encountered before a production unit can be placed in service. Any contemplated specialized application should be routed through Code 815."(1)

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(1) Original memo. dated 11 October 1950.

MANUFACTURERS

The following is an incomplete but representative list of firms manufacturing magnetic amplifiers or components thereof:

Acme Electronics*, 300 N. Lake Ave., Pasadena, California
Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin
Arma Corporation, 254 - 36th Street, Brooklyn 32, N. Y.
Bell Telephone Laboratories* (WE Co.), 120 Broadway, New York, N. Y.
Bendix Radio Company (Bendix Aviation Corp.), Towson, Md.
Bogue Electric Company, Paterson, N. J.
Collins Radio Company*, Cedar Rapids, Iowa
Computer - Research*, Torrence, California
Cook Research Laboratories*, 1457 Diversey Pkwy., Chicago 14, Ill.
Eclipse - Pioneer (Bendix Aviation Corp.), Clifton, N. J.
Engineering Research Associates, Inc.*, 1902 Minnehaha, St.Paul, Minn.
Federal Telephone and Radio Company, Clifton, N. J.
Ford Instrument Co. (Sperry Corp.), 3110 Thompson Ave,Long Is.City,N.Y.
General Electric Company*, Schenectady, N. Y.
Gilfillan Bros., Inc., Los Angeles, California
Hanson-Gorrill-Brian Inc., Glen Cove, N. Y.
Honeywell, Minneapolis, Minn.
Inet, Inc., 8655 - S. Main St., Los Angeles 3, California
I.T.E. Circuit Breaker Company, 19 Hamilton St., Philadelphia 30 Pa.
Kearfott Manufacturing Corp., 75 Hudson Street, Newark, N. J.
Lear, Inc., 110 Ionia Avenue, N.W., Grand Rapids, Michigan
Magnetics, Inc., Butler, Pennsylvania
Magnetic Amplifiers, Inc.*, 11-54 - 44th Drive, Long Is. City, N. Y.
Minnesota Electronics, St Paul, Minn.
North Electric Company, Galion, Ohio
Pacific Electric Company, Los Gatos, California
Raytheon Manufacturing Company*, Waltham, Mass.
Servomechanisms, Inc., Imperial High & Sepulveda Blvd., Los Angeles,Calif.
Sola Electric Company, Chicago, Illinois
Sperry Gyroscope Co.*, Great Neck, Long Island, N. Y.
Telemark, Inc., 100 Greyrock Place, Stamford, Conn.
Transducer Corp.*, 1085 Commonwealth Ave., Boston 15, Mass.
United Transformer Co., 150 Varick Street, New York, N. Y.
Varo Manufacturing Company, Garland, Texas
Vickers, Inc. (Sperry Corp.), 1815 Locust St., St. Louis, Missouri
Ward-Leonard Electric Company, Mt. Vernon, N. Y.
Westinghouse Electric & Manufacturing Co., Pittsburgh, Pa.
Willys - Overland Motors, Inc., Toledo 1, Ohio
Willind-Pierce Corp.*, Redondo Beach, Calif.
EDO Corp., Long Island, N.Y.

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Science,

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it: but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be."

- Lord Kelvin